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BULLETIN No. 111 — 115

APRIL, 1919

A STUDY OF THE FORMS IN WHICH
SULPHUR OCCURS IN COAL

BY

ERRATA

Intro piece to Bulletin No. 111.

Page 6, line eight: *for* "as pyrites, or marcasite sulphates," *read* "as pyrites or marcasite, sulphates."

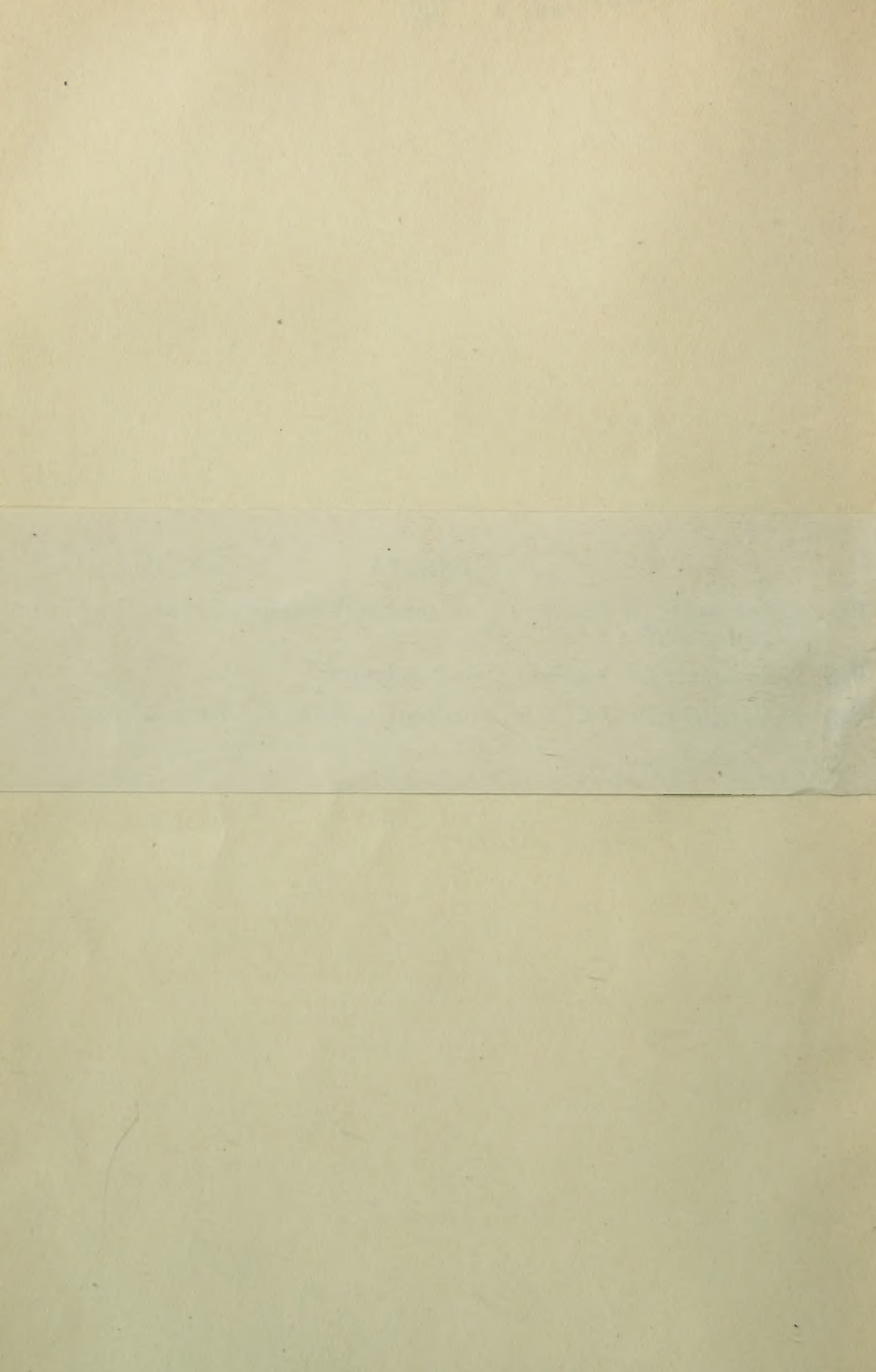
Page 35, line nine: *for* "sulphuric" *read* "sulphinic."

Page 60, line eighteen: *for* "E. F. Charlton" *read* "E. E. Charlton."

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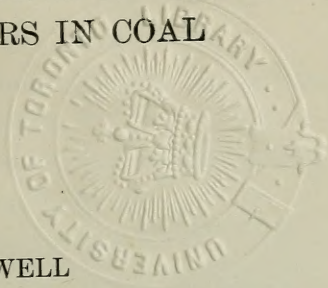
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FORMERLY STUDENT IN THE GRADUATE SCHOOL OF THE
UNIVERSITY OF ILLINOIS

WITH

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PROFESSOR OF APPLIED CHEMISTRY



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A STUDY OF THE FORMS IN WHICH SULPHUR OCCURS IN COAL

I. INTRODUCTION

1. *Present Status of Knowledge of Sulphur in Coal.*—Although carbon, hydrogen, and oxygen are generally considered to be the three important elements in coal, sulphur often forms a large portion of the coal substance.* In Illinois coals the sulphur often weighs as much or more than the quantity of hydrogen, but the behavior of these substances is radically different. The heat value of sulphur, for example, is less than one-twelfth that of hydrogen. The products of combustion moreover differ widely, the sulphur burning to an acid and the hydrogen to water. Other marked differences occur in the processes of combustion and of coking. These differences are modified to a certain extent by the original forms in which the sulphur occurs in the coal substance. From these considerations it is obvious that a knowledge of sulphur in its initial forms in coal is highly desirable.

For some time sulphur in coal has been known to be combined with iron as iron pyrites and marcasite, both of which have the formula FeS_2 . Very small quantities of sulphates also are found, but the amount is so small, especially in freshly mined coal, that it is almost negligible. Free sulphur has been suspected to be present in coal, but its presence is the exception rather than the rule. Iron pyrites is undoubtedly the chief inorganic sulphur compound found in any great quantity in coal.

There are many indications that organic sulphur compounds form a large part of the sulphur in coal, but the nature of these compounds or the amount of sulphur so combined has never been determined prior to this investigation. Since the organic sulphur had its source in the protein sulphur of the plant and animal life from which the coal was formed, it is probable that these compounds in the coal are degradation products of the original material.

Methods† for the analysis of the total sulphur of coal are numerous and need not be described here. They all depend upon the general

*See Appendix I for a historical discussion of the constitution of coal.

†See Appendix II for a historical discussion of the development of a method for analyzing the forms of sulphur in coal.

principle of completely oxidizing the sulphur to the sulphate form and then precipitating it as barium sulphate. No reliable and accurate method, however, has been devised for estimating each form of sulphur in coal. The method generally used at the present time is indirect and makes use of the following assumptions. All the sulphur in coal is assumed to be present as pyrites, or marcasite sulphates, and organic sulphur. The amount of sulphate sulphur is estimated by dilute hydrochloric acid extraction. In addition to the determination of sulphate sulphur in the extract, the iron is also determined. The remainder of the iron in the coal, which is obtained by subtracting the extract iron from the total iron, is assumed to be combined with sulphur to form pyrites. By a simple stoichiometrical calculation the pyritic sulphur may be determined. Since only three forms of sulphur were assumed to be present, the organic sulphur content is calculated by subtracting the amount of the two inorganic forms from the total sulphur.

Investigations prove that coal undergoes considerable oxidation while in storage, to some extent when it is in free contact with the air, but to a less extent when it is stored in air tight containers. The oxidation of the coal substance as a whole includes the oxidation of the sulphur in coal. The iron pyrites oxidizes to the sulphate form so that whereas fresh coal generally contains only a trace of sulphates, coal after being stored two or three years may have the major portion of the inorganic sulphur present as sulphate.

When coal is subjected to destructive distillation not in contact with air, the sulphur present divides between the residue and the volatile matter. The ratio between the residual sulphur and the volatile sulphur in coal varies between wide limits. It remains fairly constant, however, for the same coal. The factors which control this ratio are not yet determined except in a very general manner. Certain coal constituents, entirely separate from the sulphur containing compounds, may have an effect on the percentage of sulphur retained in the coke, but in all probability the decisive factor affecting the sulphur content is the relative amounts of the different sulphur forms present.

The sulphur in the volatile matter resulting from the destructive distillation of coal is in the form of hydrogen sulphide or thiophen derivatives, but the nature of the sulphur retained in the coke has never been fully determined. A portion of it is known to be present in the form of sulphides, but the larger part seems to exist in organic combination.

2. *Purpose of the Proposed Study.*—The purpose of this investigation has been to make a thorough study of the nature of the sulphur containing compounds in coal, the quantity of each form present, and the change which characteristic forms undergo when the coal is allowed to stand or is subjected to coking. It has been stated that coal was assumed to contain three types of sulphur compounds. The present investigation was undertaken to prove or disprove the presence of these types, to find out if other types exist and to devise methods for the quantitative study of each form.

With this preliminary work as a background, the changes which the sulphur in coal underwent through oxidation and the factors entering into these changes were then studied. The question of pyrites as a cause of spontaneous combustion in coal and the question of the deterioration of heating value are closely connected with the oxidation of sulphur in coal. For this reason a study of some of the conditions governing the phenomenon was of practical importance.

A practical application of the sulphur in coal study is the coking of coal. The purpose of this investigation was not only to determine some relationship between the amounts of the various sulphur forms in coal and the residual sulphur left in coke, but also to determine the nature of the sulphur retained in the coke. A knowledge of these conditions would be at least one step toward a means for controlling the sulphur content of coke.

3. *Conclusions.*—A study of the data contained hereinafter suggests the following conclusions:

(1) The sulphur of coal occurs in four characteristic forms, two of them organic and two inorganic.

(a) If the resinic organic type is shown to be organic sulphur by its lack of an ash, its presence in that portion of the organic material soluble in phenol indicates its association with that substance.

(b) The humus organic sulphur is shown to be organic by the very small amount of ash in the compounds in which it occurs. These compounds are shown to be closely related to humus substances by their chemical action.

(c) The pyritic or marcasitic sulphur is present as FeS_2 as indicated by the iron-sulphur ratio when the pyrites is oxidized and taken into solution.

(d) The sulphate sulphur is shown to be such by the fact that it dissolves in dilute hydrochloric acid as sulphate without preliminary oxidation.

All four forms have therefore been definitely proved present, and only these forms exist in the coal since the combined percentages account for all the sulphur. Free sulphur was not found in any of the samples of coal and is presumably absent except in unusual cases where it might occur in small quantities as a decomposition product of pyrites.

(2) The early method of determining the forms of sulphur in coal gives high results for the pyritic sulphur and low results for the organic sulphur. The method developed in this investigation is decidedly more nearly accurate for the analysis of the different forms of sulphur in coal.

(3) Some of the sulphur in coal, probably in the form of iron pyrites, is oxidized gradually to the form of sulphate. One of the chief factors in this reaction seems to be the length of time of standing. An excess of air has no very decisive effect upon oxidation; in fact, coal kept in a tightly stoppered flask oxidizes freely.

(4) The reaction seems to be hastened by the presence of bacteria or some catalytic agent. This influence is not evident at first, probably because of the large amount of free oxygen present in the flask.

(5) The amount of soluble sulphate formed by the reaction is less than it would be if the amount of soluble iron is taken as a criterion. This fact suggests the union of some of the oxidized sulphur with the organic matter of the coal.

(6) It seems probable from this investigation that when the coal is coked the sulphur forms of the coals change as follows:

(a) The sulphate sulphur is retained by the coke but in some form other than inorganic sulphate.

(b) The pyritic sulphur is partially volatilized and a portion is also left in the coke, probably as sulphide sulphur. All the pyrites is decomposed.

(c) Most of the resinic sulphur is left in the coke, but in a form different from that existing in the coal.

(d) The humus sulphur volatilizes partly but some is left in the coke in a changed form.

(7) The forms of sulphur in the coke were studied, but they were not fully identified. A small part of the sulphur exists as sulphide, and the remainder is probably in combination with carbon. This last form is extremely stable to strong acids, oxidizing agents and heat, but readily gives up its sulphur as hydrogen sulphide when subjected to the action of nascent hydrogen.

(8) During the coking process, secondary reactions between constituents of the coal and decomposed sulphur compounds affect the quantity of sulphur retained by the coke.

II. THE DEVELOPMENT OF A METHOD FOR ANALYZING THE DIFFERENT FORMS OF SULPHUR IN COAL*

4. *The Method Involving the Use of Organic Solvents.*—The first method used to determine the different forms of sulphur in coal was that of organic solvents for removing the organic compounds with the idea that possibly all the organic sulphur would be acted upon by the solvent employed and would be found in the extract.

The solvent which extracted the greatest amount of material was phenol. In a few cases, the amount of sulphur in this extracted material was determined, but since this was both a difficult and time-consuming procedure only the insoluble residue was analyzed for its sulphur content. The difference between the amount found and the total sulphur was the sulphur in the extract. It is seen that this procedure calls for the determination of the total sulphur. If in that connection the total iron is also determined, the assumption may be made that all the inorganic sulphur is combined with the iron either as FeS_2 or FeSO_4 . If this assumption is correct, all the factors necessary for determining the various forms of sulphur present, namely, the total sulphur, the inorganic sulphur as sulphate and pyrites and by difference, the organic sulphur, might be found in the phenol soluble extract or divided between that material and the cellulosic or insoluble residue.

This method for determining the different sulphur forms was provisional and had no exact experimental confirmation but was regarded as the best method available at the time. The analytical procedure was as follows. The percentage of all constituents was based upon the coal as weighed out for analysis. A sample of coal was obtained, together with any information concerning where and how recently it had been mined and any other facts which seemed pertinent to the investigation. No effort was made to get representative samples, since a study of the compounds in one piece of coal would give results similar to those of a mixed sample, as far as the general composition of the coal and a method of analysis were concerned. This sample was then ground to about pea-size by a rotary crusher; then the coal was spread out in a thin layer for several hours to secure in the sample the moisture conditions of the room. It was then ground to 100-mesh size and stored in an air-tight container.

*See Appendix II for a historical account of the development of a method by other investigators.

A total sulphur and a total iron determination were made on a small quantity of the sample, and on a larger quantity a determination of the sulphur and the iron which were soluble in dilute hydrochloric acid. The percentage of total iron minus the percentage of hydrochloric-acid-soluble iron was considered to be the percentage of pyritic iron in the sample. From this result pyritic sulphur was estimated, it being assumed that pyrites always has the formula FeS_2 . The sulphate sulphur was assumed to be that obtained in the hydrochloric acid extract. The organic sulphur was then taken as the difference between the total sulphur and the sum of the two inorganic forms.

The method used for determining the total sulphur and iron in the coal was that of Eschka and Fresenius. Although the results for the sulphur were fairly good, those for the iron were generally too low. A sodium peroxide fusion method, which gave excellent results, was then substituted; consequently this substitute method was used during the investigation for the analysis not only of the coal, but also for sulphur and iron in all residues.

This fusion was performed in a pure nickel crucible, having a loose fitting lid and a capacity approximating 50 cc. Some sodium peroxide was placed in the bottom, on top of which was placed the substance to be analyzed in the form of a fine powder. Sodium peroxide was then added until the crucible was about half full, the amount depending upon the quantity of coal substance used. With coal itself, half gram samples were used. The contents were thoroughly mixed by means of a glass stirring rod, and a thin layer of sodium peroxide was sprinkled over the top. The lid was put in position and held in place by a piece of metal weighing a few ounces. The charge was ignited by using a Bunsen burner to heat the outside of the crucible. Almost without exception, complete combustion of the organic matter occurred in a few seconds, without any of the charge blowing out under the lid. After the crucible had cooled somewhat, the fusion was dissolved out with water. The alkaline solution was carefully acidified with hydrochloric acid and filtered.

From this point in the analysis there was little variation from the ordinary methods of determining iron and sulphur in a solution. The hot solution was poured into a slight excess of ammonia and the mixture stirred to coagulate the ferric hydroxide. This hydroxide was filtered off and dissolved from the filter by using concentrated hydrochloric acid, and the amount of iron was determined by the usual Zimmermann-Reinhardt process. Since the quantities of iron were small in nearly

all cases, the potassium permanganate solution used was weak, its strength being about one-fortieth normal.

The filtrate from the ferric hydroxide was made slightly acid with hydrochloric acid. When it was brought to boiling 10 cc. of 10 per cent barium chloride were added slowly. The solution was heated and stirred for some time in order to prevent the passing of barium sulphate through the filter. Since this precipitate was small, a slight loss would cause a large percentage error. After filtering, the filter was ignited in a porcelain crucible and the barium sulphate weighed.

The method outlined in the preceding paragraphs varies in two particulars from the one ordinarily used. No oxidizing agent is added before precipitating the iron or the sulphur, since the sodium peroxide fusion has insured complete oxidation. A second precipitation of the iron to remove any basic sulphate is, furthermore, omitted, because the amount of precipitate as compared with the volume of the solution is so small. In order to show that a second precipitation was unnecessary and that the method used was accurate enough for the purposes of the investigation, the following experiment was performed. Two samples of pure ferrous ammonium sulphate were weighed out, one corresponding roughly to the sulphur content of one gram of a low sulphur coal, the other to that of a very high sulphur coal. The samples were dissolved in very dilute hydrochloric acid, oxidized by boiling with bromine water, and then run through the analysis just described. The results of this experiment are presented in Table 1.

TABLE I
CHECK ANALYSIS OF FERROUS AMMONIUM SULPHATE

Weight of sample.....	.0729 g.	.3080 g.
Theoretical per cent iron.....	14.3	14.3
Per cent iron determined.....	14.4	14.2
Theoretical per cent sulphur.....	16.4	16.4
Per cent sulphur determined.....	16.5	16.3

It will be noted that the variation between the theoretical and actual determination is very small. If larger samples had been used, the relative error would probably have been still smaller. Considering the error for the size of the samples of coal used, the error when using large samples would not be greater than 0.01 per cent. Since no conclusions are drawn within this amount, the method is suited to the conditions of the work.

The sulphur and the iron of coal soluble in dilute hydrochloric acid were determined from samples of the coal weighing 5 grams. These

samples were treated with 300 cc. of 3 per cent hydrochloric acid. This mixture was allowed to digest at 60 degrees Centigrade for 40 hours. The solution containing the soluble iron and sulphate sulphur was filtered off and oxidized by means of bromine water. Analyses were then made for both sulphur and iron by the method previously described. This method of extraction is accurate for the determination of sulphates. It does not determine other sulphur forms present, however, as shown by the fact that coals known to contain large quantities of pyritic and organic sulphur yielded no sulphur whatever by this means of extraction.

These methods when used as described will determine the percentage of the different forms of sulphur in coal, provided the assumptions previously made are correct.

The next step in the investigation, namely, the extraction of the coal with phenol, was made in a manner slightly different from that usually employed. Instead of dropping hot condensed phenol upon the coal in an extraction thimble, a flask containing both the finely powdered coal and the phenol was heated to 140 degrees Centigrade by an electric oven. A one-half gram of coal was placed in a 100 cc. Erlenmeyer flask. An air condenser about two feet long was placed in the neck of the flask with the condensing tube extending through the top. Twenty-five cubic centimeters of molten phenol were poured upon the coal. The flask was placed in the inner chamber of the electric oven and heated at a temperature of 140 degrees Centigrade for 20 hours, after which it was removed and the contents promptly filtered through a Gooch crucible. The flask was thoroughly rinsed with alcohol to remove any particles of residue and to dissolve the excess phenol from the residue in the crucible. An ether washing followed, the residue being allowed to dry in the crucible.

In a few cases, as mentioned in the foregoing, the extract was analyzed for its sulphur content, but the method was difficult and time-consuming. When such an analysis was made, the dark red extract was evaporated in a porcelain dish heated by the electric oven. When almost all the phenol had been driven off, the dish was allowed to cool and the remaining substance was carefully removed with a spatula. The substance was finely powdered and fused with sodium peroxide in order to get the sulphur into solution to analyze. To prevent the oxidation of the extracted substance while in the oven, a slow stream of carbon dioxide was passed through the heating chamber.

The most convenient way of determining both the residual and the

extracted sulphur, however, was the analysis of the insoluble residue. The residue was emptied from the Gooch crucible and mixed thoroughly with sodium peroxide. The analysis from this point was the same as that for the total sulphur in coal. Care had to be taken to make the asbestos mat as thin as possible, since the subsequent fusion with sodium peroxide took most of the asbestos into solution and trouble might be encountered later with the silicic acid when the barium sulphate was precipitated. With this precaution observed, the solution did not need to be evaporated to remove the silicic acid, since it does not precipitate with barium in dilute solutions.* The difference between this residual sulphur as thus determined and the total sulphur was the sulphur extracted by the phenol.

5. *Description of Apparatus Used.*—A cross-section of the electric oven especially constructed for the phenol solution experiments in this investigation is shown in Fig. 1. The cylindrical casing of galvanized iron was made 14 inches high and 12 inches in diameter. The inner chamber was a cylinder of heavy iron, 10 inches high and 5 inches in diameter, wrapped with asbestos paper and "nichrome" resistance wire in the form of a coil. Fifty feet of No. 20 wire was wrapped into a one-quarter-inch coil, doubled at the middle and coiled around the cylinder ten times so that the two ends came out at the top. On top of this wire a one-half-inch layer of fireclay-water glass mixture was placed, and the space between the inner chamber and the casing was filled with an asbestos-magnesia compound. An alternating current of 110 volts was used, and with no other resistance than the wire of the oven the current flowing was 3.1 amperes. In order to keep the temperature down to the 140 degrees desired, it was necessary to put lamps in the circuit for resistance.

In the experiments by Parr and Hadley on phenol extraction, an effort was made to exclude air from the extraction chamber by the use of a stream of carbon dioxide. The method used in the present investigation did not require this precaution as shown by the following experiment. Two flasks were used, one of which had the air condenser open at the top as usual. The other was closed by connecting it to a U tube containing alkaline pyrogallol. This U tube was attached to another containing water. The air was pumped from the flask and allowed to return through the two U tubes; thus only nitrogen was in the extraction

*Hillebrand, W. F., "Mineralogical Notes," U. S. Geological Survey, Bul. 167, p. 73, 1900.

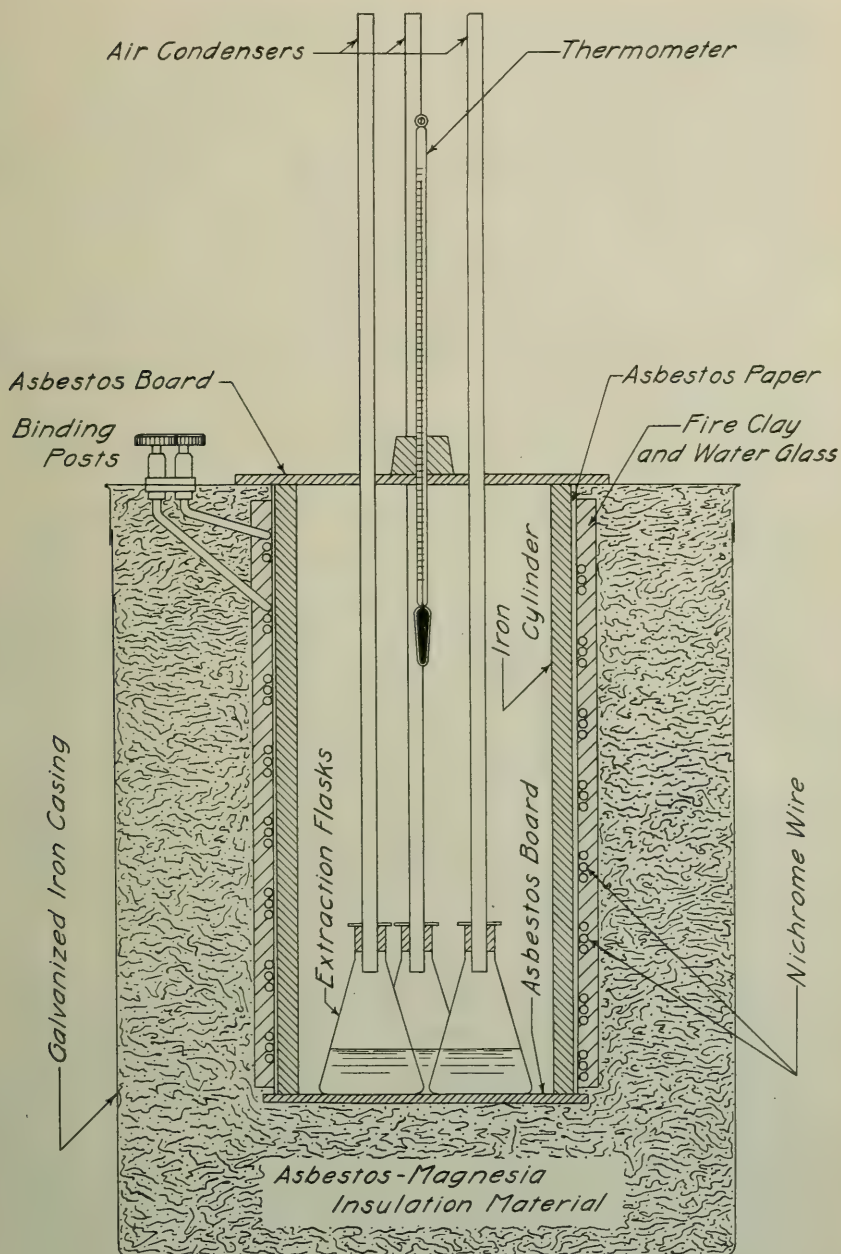


FIG. 1. CROSS-SECTION OF ELECTRIC FURNACE USED IN PHENOL EXTRACTION OF COAL

flask during the entire process. After the usual process of extraction these results were obtained:

Total sulphur in coal	2.18 per cent
Residual sulphur with open condenser	2.03 per cent
Residual sulphur with nitrogen atmosphere . .	2.06 per cent

In several other cases the same test was applied and no essential difference in results was noticed; consequently the open end condenser was used in nearly all the extraction work.

6. *Description of Coal Samples Tested.*—Ten different coals were studied during the investigation. A brief description of each is presented as follows:

Coal No. 1. A Vermilion County coal taken from an Illinois Traction Company car in October, 1915.

Coal No. 2. A Vermilion County coal obtained from a mine near Georgetown, May 19, 1915.

Coal No. 3. A Vermilion County coal collected from Kelly No. 4 mine at Westville, March, 1916.

Coal No. 4. A Vermilion County coal obtained from the Danville Colliery Company at Catlin, October 25, 1916.

Coal No. 5. A Saline County coal mined near Harrisburg, April 1, 1915.

Coal No. 6. A Vermilion County coal secured from the Danville Electric Mine, June 10, 1915.

Coal No. 7. A Vermilion County coal secured from the Danville Colliery Company at Catlin, February 3, 1917.

Coal No. 8. A Tennessee coal of the Jellico type, known as "Black Beauty," obtained about May, 1917.

Coal No. 9. A Japanese coal containing large clumps of resinous material, mined December, 1913.

Coal No. 10. A Tennessee coal of the Jellico type obtained April 1, 1915.

Seven of the ten coals used were from Illinois, one of these coming from Saline County and the other six from Vermilion County. The Vermilion County coals were most suitable for the investigation, since their sulphur content was generally high and they contained comparatively large amounts of the different sulphur forms. Eastern anthracites were not analyzed since they contain little sulphur.

The samples were put in air-tight containers on the days they were obtained and studied at times over a period varying from one day to almost three years. The variation in the age of the samples was advantageous since a great variety of data concerning the sulphate

formed could be obtained. Sulphate sulphur, for example, increases rapidly in most coals during storage; consequently the hydrochloric-acid-soluble iron and sulphur were redetermined before each set of data on a coal was secured.

The proximate analysis of each of these coals is given in the following table.

TABLE 2
PROXIMATE ANALYSES OF COALS
(Values given in per cent)

Sample Number	Moisture	Volatile Matter	Fixed Carbon	Ash
1	6.77	41.37	43.48	8.38
2	4.26	34.24	45.29	16.21
3	11.37	35.85	47.83	4.95
4	5.98	42.82	45.90	5.30
5	4.72	34.73	54.29	6.26
6	5.54	38.36	40.13	15.97
7	2.69	42.81	45.05	9.45
8	1.63	37.39	58.22	2.76
9	2.05	44.47	42.40	11.08
10	3.53	35.97	59.54	0.96

The analyses for sulphur and iron on each of the coals, calculated on an air dry basis,* are given in Table 3.

TABLE 3
SULPHUR AND IRON CONTENT OF COALS
(Values given in per cent)

Sample Number	Total Sulphur	Total Iron	HCl sol. Sulphur	HCl sol. Iron
1	2.68	1.36	0.04	0.14
2	2.18	1.65	0.17	0.27
3	0.64	0.21	0.00	0.06
4	2.14	0.69	0.05	0.07
5	1.20	0.55	0.25	0.20
6	5.00	3.40	1.31	1.62
7	3.31	1.87	0.01	0.07
8	1.02	0.82	0.01	0.12
9	1.40	0.95	0.02	0.29
10	0.94	0.38	0.02	0.11

In this table an effort has been made to show the percentage of hydrochloric-acid-soluble sulphur and iron when the phenol extraction was made. As previously mentioned, these values change somewhat rapidly; so this determination was repeated at intervals during the progress of the investigation.

*Unless otherwise stated, all percentages through the investigation are referred to the basis of the air dried coal.

7. *Results Obtained by Organic Solvent Methods.*—Table 4 gives the results of phenol extraction of these coals and a comparison with the organic and inorganic forms of sulphur in the coal as calculated from the foregoing data. The method used in calculating these forms of sulphur has been indicated, but it may be repeated in a more definite manner. The pyritic sulphur, that is, the sulphur combined as iron pyrites or marcasite, was deduced by subtracting the soluble iron from the total iron and then multiplying this result by 1.145 which is the chemical factor for calculating the equivalent of sulphur combined with the iron when the two are associated as pyrite. The sulphate sulphur was considered the same as the soluble sulphur.

TABLE 4

COMPARISON OF SULPHUR EXTRACTED BY PHENOL WITH ORGANIC SULPHUR
(Values given in per cent)

Sample Number	A Total Sulphur	B Sulphur as FeS ₂	C Sulphur as Sulphate	D Total Organic S by Difference, i. e., A—(B+C)	E Organic S: Soluble in Phenol	F Difference between Total Organic S and Phenol Soluble S
1	2.68	1.39	0.04	1.25	0.42	0.83
2	2.18	1.58	0.17	0.43	0.15	0.28
3	0.64	0.17	0.00	0.47	0.20	0.27
4	2.14	0.71	0.05	1.38	0.34	1.04
5	1.20	0.40	0.25	0.55	0.16	0.39
6	5.00	2.03	1.31	1.66	0.77	0.89
7	3.31	2.06	0.01	1.24	0.50	0.74
8	1.02	0.80	0.01	0.21	0.10	0.11
9	1.40	0.75	0.02	0.63	0.21	0.42
10	0.94	0.31	0.02	0.61	0.12	0.49

It may easily be seen from this table of experimental results that no relationship whatever exists between the amount of sulphur extracted by the phenol and the amount calculated to be present as organic sulphur, except that the latter is always considerably larger than the former. This difference in results may be due to any one of several conditions. The phenol may not extract all the organic sulphur compounds, or the sulphur may be present in some undetermined inorganic form. The standard of comparison has, moreover, not been definitely proved correct, for the iron considered to be pyritic iron may be combined with more sulphur than the theoretical amount for pyrite, or it may be combined with less sulphur as in coal which contains iron silicate.

A wide gap exists between the supposedly organic sulphur calculated by difference (column D) and the phenol soluble sulphur (column E)

which is known to be organic in character. That the phenol extracted sulphur is organic in nature cannot be doubted since the extract is practically ashless, and organic sulphur only must, therefore, be present. Two questions remain to be answered: first, is the iron, assumed to be combined as pyrites, quantitatively present as such, and secondly, what is the nature of that sulphur assumed to be organic and not extracted by phenol, the quantity of which is probably represented for each coal in the last column of Table 4?

To determine the nature of the sulphur assumed to be organic and not extracted by phenol, other solvent methods were used. Higher temperature or longer time than had been used for extraction by the phenol was not considered practicable according to previous research. As far as the amount of sulphur extracted was concerned, the method used in this investigation was as good or even better than the extraction thimble process of Parr and Hadley and of Charlton, as shown by a comparison of the two methods on the same coals. In every case the percentage of sulphur extracted by the phenol was slightly greater when determined by the method here described. Since no additional help could be obtained from phenol extractions of coal, other solvents were sought to extract the coal sulphur compounds.

Among these solvents pyridin and anilin have been used in a study of the constitution of coal. Since the amount of sulphur extracted by these solvents had not been investigated, some experiments of this nature seemed essential to the investigation; consequently a sample of coal No. 1 was extracted with pyridin and another with anilin. In these qualitative tests approximately the same amount of sulphur appeared in the extract as when phenol was used. These solvents, like phenol, had no effect on iron pyrites and calcium sulphate. In order to test them quantitatively, 0.5 gram samples of coals Nos. 1 and 3 were extracted with 25 cc. of anilin, the same method of procedure

TABLE 5
SULPHUR EXTRACTED BY ANILIN
(Values given in per cent)

Sample Number	Total Organic S by Difference	Organic S Soluble in Phenol	Organic S Soluble in Anilin	Difference between Total Organic S and Anilin Soluble S
1	1.25	0.42	0.44	0.81
3	0.47	0.20	0.09	0.38

being followed as with phenol. The temperature of the extraction was 140 degrees Centigrade. The results are given in Table 5.

Compared with the results obtained by the phenol extraction, the results are about the same for No. 1. For coal No. 3, however, they are not so good. No conclusions can be drawn from this experiment regarding the anilin soluble sulphur constituents being the same as those of the phenol soluble.

Another extraction experiment was tried in which a mixture of equal parts of phenol and aniline were used as the solvent. The conditions for this determination were the same as those for the preceding experiment. The following table gives the result.

TABLE 6
SULPHUR EXTRACTED BY PHENOL AND ANILIN
(Values given in per cent)

Sample Number	Total Organic S by Difference	Organic S Soluble in Phenol	Organic S Soluble in Phenol and Anilin	Difference between Total Organic S and Phenol-Anilin Soluble S
1	1.25	0.42	0.53	0.72

This experiment seemed to give better results than the preceding one, but the sulphur unaccounted for was still too great to regard this method as of practical value. Theoretically it was interesting, since it indicated that constituents might be extracted by the basic aniline different from those extracted by the acid-like phenol.

The extractions with pyridin had to be made at a temperature lower than that made with phenol and anilin, because of the lower boiling point of this solvent. The temperature chosen was 85 degrees Centigrade. The results are given in Table 7.

TABLE 7
SULPHUR EXTRACTED BY PYRIDIN
(Values given in per cent)

Sample Number	Total Organic S by Difference	Organic S Soluble in Phenol	Organic S Soluble in Pyridin	Difference between Total Organic S and Pyridin Soluble S
1	1.25	0.42	0.35	0.90
2	0.43	0.15	0.13	0.30

The sulphur extracted by pyridin is less than that removed by phenol; hence its use as a solvent was discarded. Benzene was tried as a solvent, but it also proved ineffective. From the experimental data given, the task of removing all the organic sulphur by means of an organic solvent seemed hopeless. Inorganic solvents were next used.

8. *Methods Involving the Use of Inorganic Solvents.*—The first inorganic solvent tried was sodium hydroxide. A sample, 0.5 g., of coal was extracted with phenol. The residue was then treated with 50 cc. of 5 per cent sodium hydroxide, allowed to stand at room temperature for 48 hours and filtered. The filtrate was then oxidized by means of sodium peroxide. An extraction of only 0.23 per cent of sulphur was secured from coal No. 1, having 0.83 per cent unaccounted for, and 0.39 per cent from coal No. 2 with 0.28 per cent unaccounted for. From these results it seemed evident that sodium hydroxide would not extract all the organic sulphur.

The second inorganic solvent tried was potassium permanganate, which according to qualitative tests has a noticeable solvent action on iron pyrite. It reacted also rather quickly on coal and took a quantity of sulphur into solution. The permanganate decolorized quickly in both cases and large quantities of manganese dioxide were precipitated. In no case, however, did the sulphur extracted by the permanganate approach in amount that of the pyritic sulphur, perhaps because of the ready reaction of the coal substance with the permanganate; hence repeated treatments were necessary to insure complete oxidation of the pyrites. Such discordant and inconclusive results were obtained and such large quantities of manganese dioxide were precipitated that this method was abandoned.

Concentrated nitric acid was the solvent next tried. This was known to be a complete solvent for the pyrites. Whether it would attack and take into solution the more stable organic sulphur compounds of the coal had to be determined. Gram samples of the coals were placed in beakers and covered with 25 cc. of concentrated nitric acid. After twenty-four hours of extraction, the percentages of sulphur given in Table 8 were found in the filtrate.

These results show that the nitric acid did not extract all the pyritic and sulphate sulphur as was assumed it would. The shortage might be attributed to extraction at room temperature. On the other hand the amount of calculated pyritic and sulphate sulphur may be high because

TABLE 8
CONCENTRATED NITRIC ACID EXTRACTION OF COAL
(Values given in per cent)

	Coal No. 1	Coal No. 2	Coal No. 4
Sulphur in HNO ₃ Extract.....	1.20	1.47	0.41
Pyritic and Sulphate Sulphur as indicated from the iron present.....	1.43	1.75	0.76

of an incorrect assumption concerning the form in which the iron occurs. A negative result seems to be obtained in attempting to find if any of the organic sulphur was oxidized and taken into solution. At least the data in Table 8 indicate that scarcely any organic sulphur was affected.

All the experiments performed would tend to show that the sulphur unaccounted for is combined in an extremely stable form. The failure of nitric acid to extract all the pyritic and sulphate sulphur would particularly indicate this tendency. Free sulphur, however, might be left in the residue after the extraction with nitric acid. In order to determine this free sulphur the nitric acid treatment just described was repeated. The residue was then boiled with pure carbon tetrachloride to remove any possible free sulphur. The carbon tetrachloride was evaporated, and the slight residue left was mixed with benzoic acid and fused with sodium peroxide. This fusion was added to the nitric acid extract and the sulphur determined. By this modified method, the sulphur in the extract of coal No. 1 was raised 0.02 per cent and that of coal No. 2 raised 0.08 per cent. The formation of free sulphur during the nitric acid treatment accordingly seems of minor importance.

The only common inorganic substances which might conform to the conditions as thus given are certain sulphides and a few insoluble sulphates. After a sodium peroxide fusion of coal No. 4 was made, acidified with hydrochloric acid and passed in hydrogen sulphide, no precipitate except a little free sulphur was obtained. This experiment proved the absence of arsenic or any other metal which might make an insoluble sulphide. An excess of sulphuric acid was added to another portion of sodium peroxide fusion solution, but no precipitate was observed; thus the absence of metals forming insoluble sulphates was shown. By a process of elimination, therefore, it was essentially proved that the unknown sulphur of the coal was of some organic form, this fact being shown by experiments hereinafter described.

Although the concentrated nitric acid had proved a failure as a solvent for stable organic sulphur, it was an excellent solvent for the two inorganic forms, namely, the sulphate sulphur and the pyrites. The data given in Table 8 seemed to indicate that not all the pyritic sulphur was being extracted by the concentrated nitric acid. That all the pyrites was extracted and that the difference in percentages was due to false assumptions in the calculation of the pyritic sulphur will be shown later.

The method used in treating the coals with the concentrated acid was very simple. Twenty-five cubic centimeters of concentrated nitric acid were poured over one gram of coal and the mixture allowed to stand twenty-four hours before filtration and analysis of the extract. The results thus obtained are given in Table 9 together with the percentage of the combined pyritic and sulphate sulphur, as estimated by the old indirect method, and the total iron in the coal.

TABLE 9
CONCENTRATED NITRIC ACID EXTRACTION OF COAL
(Values given in per cent)

Sample Number	Sulphur in Acid Extract	Iron in Acid Extract	Pyritic Sulphur (as calculated from supposedly Pyritic Iron ¹) plus Sulphate Sulphur in Coal	Total Iron in Coal
7	1.72	1.53	2.07	1.87
7	1.76	1.52	2.07	1.87
7	1.77	1.51	2.07	1.87
7	1.72	....	2.07	....
7	1.77	....	2.07	....
7	1.69	....	2.07	....
4	0.65	0.62	0.76	0.69
4	0.65	0.58	0.76	0.69

If the method for calculating the pyritic sulphur as indicated from the iron present were correct, the two iron values and the two sulphur values should correspond, or the nitric acid extract sulphur percentage should be a little higher than the iron percentage because of partial oxidation of the organic sulphur. The calculated values, however, are all high as compared with those obtained directly.

Some doubt existed whether all the pyrites was being taken into solution by the nitric acid; consequently a series of experiments was begun to determine the effect of aqua regia on the coal. The method

¹Pyritic Iron = Total Iron minus HCl Soluble Iron.

adopted was similar to that which made use of nitric acid, except that heat was applied to hasten the solution process, the time for which was reduced to about one hour. The solvent used consisted of one part of concentrated hydrochloric acid and three parts of concentrated nitric acid. Where only 0.65 per cent of sulphur had been extracted from coal No. 4 by means of nitric acid, the hydrochloric-nitric acid treatment yielded 0.74 per cent in a very short time, and 0.90 per cent during several hours on the water bath. Several coals were treated, and the results of these extractions are given in Table 10.

TABLE 10
HYDROCHLORIC-NITRIC ACID EXTRACTION OF COAL
(Values given in per cent)

Sample Number	Sulphur in Acid Extract	Iron in Acid Extract	Pyritic Sulphur (as calculated from supposedly Pyritic Iron ¹) plus Sulphate Sulphur in Coal	Total Iron in Coal
4	0.89	.....	0.76	.....
4	0.91	.....	0.76	.....
8	0.30	.....	0.81	.....
8	0.29	.....	0.81	.....
5	0.57	0.44	0.65	0.55
5	0.61	0.48	0.65	0.55
7	2.08	1.58	2.07	1.87
7	2.12	1.58	2.07	1.87
9	0.42	0.50	0.77	0.95
9	0.40	0.52	0.77	0.95
6	3.95	3.34	3.34	3.40
6	3.95	3.29	3.34	3.40

Several interesting conclusions may be drawn from this table of data. Without much doubt the strong solvent action of hot hydrochloric-nitric acid mixture established the presence of all the non-silicate iron in the filtrate. The silicate iron must then be considered the difference between the total iron and that in the filtrate. This difference is shown in the second and fourth columns of Table 10. In the case of coals Nos. 7 and 9, the amount of silicate iron is large. The error that this amount would cause in a pyritic sulphur determination by calculation from the iron present would be large. The data in Table 10 show that in some cases there is more sulphur in the extract than calculated to be present as pyritic and sulphate sulphur. Since the existence of silicate iron would reverse this discrepancy, the excess sulphur must be part of that organically combined, oxidized and taken into solution by the strong oxidizing solvent.

¹Pyritic Iron = Total Iron minus HCl Soluble Iron.

As previously stated, the iron extracted by the acid mixture is almost certainly the non-silicate iron, or in other words the sum of the pyritic iron and the iron soluble in dilute hydrochloric acid. If from this sum the dilute acid soluble iron is subtracted, only the pyritic iron will be left and from this the exact amount of pyritic sulphur may be determined. Table 11 gives a comparison of the percentages of pyritic sulphur obtained by this method and by the method using the total iron minus the dilute acid soluble iron as representing the pyritic iron, and also gives the sulphur determined in the hydrochloric-nitric acid extract minus the sulphur soluble in dilute hydrochloric acid.

TABLE 11
COMPARISON OF PYRITIC SULPHUR DETERMINATIONS ON COALS BY
DIFFERENT METHODS
(Values given in per cent)

	Coal No. 5	Coal No. 6	Coal No. 7	Coal No. 9
Pyritic S calculated from Pyritic Fe. (Pyritic Fe = HCl plus HNO ₃ sol. Fe. minus dilute HCl sol. Fe.)	0.30	1.94	1.72	0.25
Pyritic S calculated from Pyritic Fe. (Pyritic Fe = Total Fe. minus dilute HCl sol. Fe.)	0.40	2.03	2.06	0.75
Pyritic Sulphur by analysis. (Pyritic S = HCl plus HNO ₃ sol. S minus dilute HCl sol. S.)	0.34	2.64	2.09	0.39

This comparison of results shows that both the amount of pyritic sulphur obtained by the older method of calculation from the total iron and the amount of pyritic sulphur obtained directly from the hydrochloric-nitric acid extraction are higher than that obtained by calculation from the iron soluble in hydrochloric-nitric acid. The high results of the method of calculation from the total iron are due to the presence of greater or less quantities of silicate iron, and the high results of the direct hydrochloric-nitric acid extraction of pyritic sulphur are due to the oxidation of a part of the organic sulphur. A method was sought to obviate the oxidation of this organic sulphur in order to determine the sulphur in the resultant extract directly as pyritic sulphur (plus the sulphate sulphur). The results produced would give separately the inorganic and organic forms of sulphur.

An experiment to make separate determinations of organic and inorganic sulphur by means of bromine was run on Coal No. 9,* but the results obtained were as unsatisfactory as those secured with the hydro-

*For a description of similar experiments by T. M. Drown see page 58.

chloric-nitric acid mixture. The bromine extraction apparently oxidized some of the organic sulphur as Ferdinand Fisher* found in his experiments.

A systematic search was conducted for a solvent which would dissolve the pyrites but not the organic sulphur. The plan followed is here briefly outlined. Samples of one of the analyzed coals were weighed out and extracted with dilute hydrochloric acid to remove all the sulphate sulphur and soluble iron. Sometimes the coal was also extracted with phenol; thus the resinic substances which appeared to oxidize rather readily under the action of oxidizing solvents were removed. Any solvent acting on this residue now took into solution only pyritic iron and sulphur either in the form of pyrites or organic sulphur, since these were the only possible forms remaining. Concentrated acid solvents acting on the residue for a long time would dissolve any silicate iron present, but the conditions were always such that they prevented dissolution. The next step was to treat the residue with the solvent for a stated length of time, filter, and analyze the filtrate for sulphur and iron. Since pyritic iron could be the only possible iron in the filtrate, the amount of pyritic sulphur may be calculated and compared with the sulphur actually in the filtrate. If these two values are the same and this relationship holds for different percentages of iron in the extract, only one conclusion is possible—that pyritic sulphur and only pyritic sulphur is being taken into solution.

The first experiment tried was preliminary and was a check determination using iron pyrites. A small quantity of finely powdered crystalline iron pyrites was mixed with some of coal No. 3. This coal was chosen because it had a very low sulphur content and would furnish the coal substance proper with very little organic sulphur. The sample was first extracted with dilute hydrochloric acid to remove all soluble iron and sulphur. The mixture now corresponded to a high sulphur coal, with nearly all the sulphur present as pyrites. One-half gram samples of this mixture were extracted with 15 cc. of hydrochloric-nitric acid mixture for a few minutes, diluted, filtered, and the filtrate analyzed for iron and sulphur. The results obtained, expressed in percentages of the original weight of the sample, are given in Table 12.

The different amounts of iron in the extracts result from the difference in activity of the beginning of the reactions, which were allowed to proceed for only a few minutes. These different amounts show that iron pyrites was extracted during every phase of the reaction. The

*See page 59.

TABLE 12

EXTRACTION OF COAL-IRON PYRITES MIXTURE WITH HYDROCHLORIC-NITRIC ACID
(Values given in per cent)

Sample Number	Iron in Acid Extract	Sulphur in Acid Extract	Pyritic Sulphur Calculated from Iron in Acid Extract as Pyritic Iron
1	1.67	1.94	1.91
2	1.34	1.53	1.53
3	1.30	1.44	1.48
4	1.30	1.51	1.48

similarity between the amount of sulphur in the acid extract and the amount as calculated from the iron in the acid extract leaves no doubt concerning this fact.

The next experiment was performed with coal No. 7. The effect of the hydrochloric-nitric acid treatment on this sample is shown in the following table. The extractions were allowed to proceed for different lengths of time; so varying quantities of pyrites would be extracted.

TABLE 13

EXTRACTION OF COAL NO. 7 WITH HYDROCHLORIC NITRIC ACID
(Values given in per cent)

Time of Extraction	Iron in Acid Extract	Sulphur in Acid Extract	Pyritic Sulphur Calculated from Iron in Acid Extract as Pyritic Iron
1 min.	0.30	0.37	0.34
2½ min.	0.53	0.76	0.61
5 min.	0.54	0.90	0.62
10 min.	0.77	1.32	0.88

This table shows experimental results already conjectured: viz., that so strong an oxidizing solution as hydrochloric-nitric acid not only attacks the pyrites but also oxidizes the organic sulphur. Attention is called to the increasing difference between corresponding figures in the last two columns as the time of extraction increases. This observation is evidence of the oxidation of sulphur other than that present in the pyritic form.

This relationship is expressed graphically by the series of curves shown in Fig. 2. The curve representing the sulphur in the acid extract rises much faster than the one showing the amount of sulphur calculated on the assumption that only pyrites is taken into solution. The lowest curve shows the amount of iron dissolved as a measure of the pyrites.

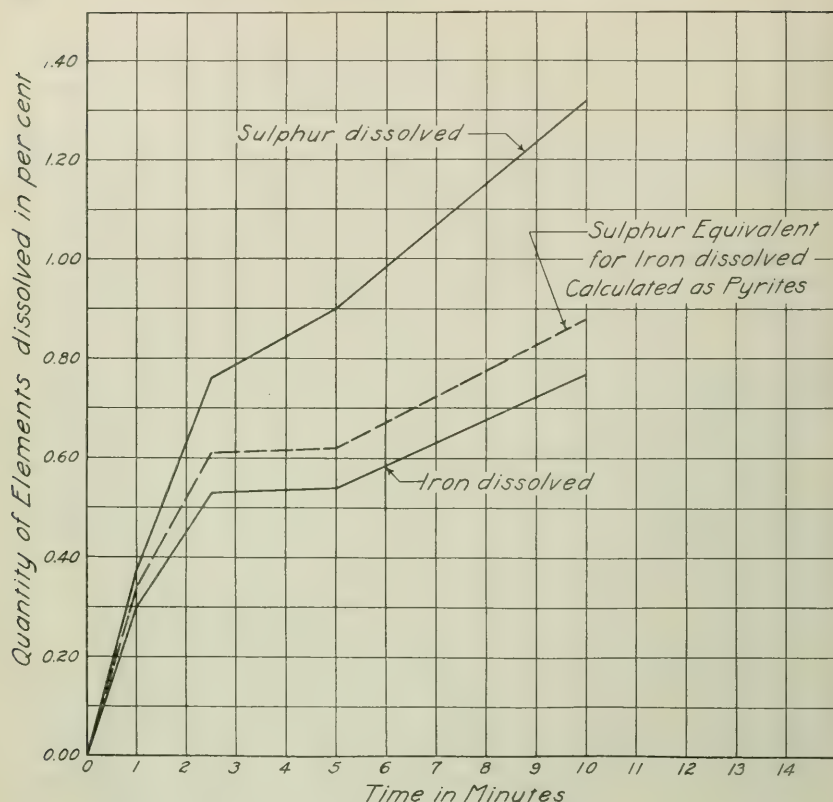


FIG. 2. CURVES SHOWING RESULTS OF THE EXTRACTION OF COAL NO. 7 WITH CONCENTRATED HYDROCHLORIC-NITRIC ACID

Table 14 shows the effect of concentrated nitric acid alone on coal No. 7.

TABLE 14

EXTRACTION OF COAL NO. 7 WITH CONCENTRATED NITRIC ACID

(One gram of coal used. Values given in per cent)

Time of Extraction	Iron in Acid Extract	Sulphur in Acid Extract	Pyritic Sulphur Calculated from Iron in Acid Extract as Pyritic Iron
2½ min.	0.90	1.05	1.03
5 min.	1.04	1.18	1.19
10 min.	1.05	1.16	1.20

These results make it appear that concentrated nitric acid is the most satisfactory solvent. Using two-gram samples of the coal, however, and allowing the extraction to proceed for a longer time gave the results shown in Table 15.

TABLE 15
EXTRACTION OF COAL NO. 7 WITH CONCENTRATED NITRIC ACID
(Two grams of coal used. Values given in per cent)

Time of Extraction	Iron in Acid Extract	Sulphur in Acid Extract	Pyritic Sulphur Calculated from Iron in Acid Extract as Pyritic Iron
1 min.	0.92	1.18	1.05
15 min.	1.01	1.35	1.15
30 min.	0.99	1.36	1.13
60 min.	1.00	1.36	1.14

These results indicate that concentrated nitric acid will attack the organic sulphur compounds as suggested by the difference between the corresponding figures in the last two columns; hence concentrated nitric acid does not make an ideal solvent for iron pyrites.

It was found convenient in such experiments to extract a quantity of coal with dilute hydrochloric acid* and then weigh out one-gram portions for each of the various solvent treatments, instead of extracting each sample separately. The analyses of some of these extracted coals are given in Table 16.

TABLE 16
SULPHUR AND IRON CONTENT OF COALS AFTER EXTRACTION WITH DILUTE
HYDROCHLORIC ACID
(Values given in per cent)

Sample Number	Total Iron	Total Sulphur
5	0.44	1.08
6	2.22	4.00
7	1.62	3.13

In the following experiment, an effort was made to lessen the violent initial reaction between the nitric acid and the coal in order to reduce the action on the organic sulphur. The concentrated nitric acid was diluted with an equal volume of water and the solution was added to the coal when brought to a temperature considerably below that of the room. The results obtained with coal No. 6 are given in Table 17.

*Unless otherwise mentioned, it will be understood that this hydrochloric acid extracted material was used in all subsequent experiments. One-gram samples were generally used.

TABLE 17
EXTRACTION OF COAL NO. 6 WITH COLD NITRIC ACID
(Values given in per cent)

Time of Extraction	Iron in Acid Extract	Sulphur in Acid Extract	Pyritic Sulphur Calculated from Iron in Acid Extract as Pyritic Iron
1 min.	1.67	1.97	1.91
15 min.	1.72	2.11	1.97
30 min.	1.72	2.25	1.97
60 min.	1.76	2.30	2.01

The excess of sulphur in the extract clearly indicates that even under the conditions of this experiment the organic sulphur is oxidized.

9. *Results Obtained with Dilute Nitric Acid as a Solvent.*—Samples of coal No. 7 were extracted with various dilutions of nitric acid for about 20 minutes. The first column in Table 18 gives the number of volumes to which one volume of concentrated nitric acid was diluted.

TABLE 18
EXTRACTION OF COAL NO. 7 WITH VARIOUS DILUTIONS OF NITRIC ACID
(Values given in per cent)

Dilution	Iron in Acid Extract	Sulphur in Acid Extract	Pyritic Sulphur Calculated from Iron in Acid Extract as Pyritic Iron
1	1.09	1.43	1.24
2	1.13	1.32	1.29
4	0.62	0.67	0.71
8	0.25	0.24	0.29

The last two dilutions gave very little sulphur in the extract and are probably too low. The dilution of the concentrated nitric acid to two volumes gave fairly good results, but the dilution to four volumes appeared to be the one which seemingly had no oxidizing effect on the organic sulphur. This experiment showed that concentrated nitric acid diluted to four times its volume, with sp. gr. of 1.12, possessed the maximum solvent effect on iron pyrites without attacking the organic sulphur. All subsequent extractions for pyritic sulphur were made with this strength of nitric acid.

Table 19 gives the results obtained by the use of this solvent on various hydrochloric acid extracted coals. All were treated at room temperature.

TABLE 19
EXTRACTION OF COALS WITH DILUTE NITRIC ACID
(Values given in per cent)

Sample Number	Time of Extraction	Iron in Acid Extract	Sulphur in Acid Extract	Pyritic Sulphur Calculated from Iron in Acid Extract as Pyritic Iron
7	1 hr.	1.12	1.23	1.28
7	18 hr.	1.16	1.29	1.33
7	72 hr.	1.13	1.30	1.29
7	10 days	1.20	1.36	1.37
5	4 days	1.80	2.06	2.06
5	4 days	1.80	2.06	2.06
5	4 days	0.27	0.31	0.31
9	4 days	0.15	0.16	0.17
9	4 days	0.15	0.16	0.17
10	4 days	0.08	0.10	0.09
10	4 days	0.08	0.10	0.09

Although several types of coal of widely varying sulphur content were treated, the amount of sulphur in each of the extracts and the amount of sulphur calculated to make FeS_2 were in every case nearly the same, as shown by the figures in the last two columns in Table 19. Dilute nitric acid is, therefore, a selective solvent for iron pyrites. The relationship between the sulphur extracted by the acid and the pyritic sulphur calculated from the iron extracted by the acid is shown graphically for coal No. 7 by the curves in Fig. 3.

The following experiment was performed to determine the best conditions for the dilute nitric acid extraction. Three samples of coal No. 7 were extracted with the dilute nitric acid; one was boiled for fifteen minutes, another was heated on the steam bath for four hours, and a third was allowed to stand at room temperature for four days. Results as shown in Table 20 were obtained.

TABLE 20
EXTRACTION OF COAL NO. 7 WITH DILUTE NITRIC ACID
(Values given in per cent)

Conditions of Extraction	Iron in Acid Extract	Sulphur in Acid Extract	Pyritic Sulphur Calculated from Iron in Acid Extract as Pyritic Iron
Boiled for 15 minutes.....	1.06	1.49	1.21
Steam bath for 4 hours.....	1.14	1.53	1.30
Room temperature for 4 days...	1.14	1.32	1.30

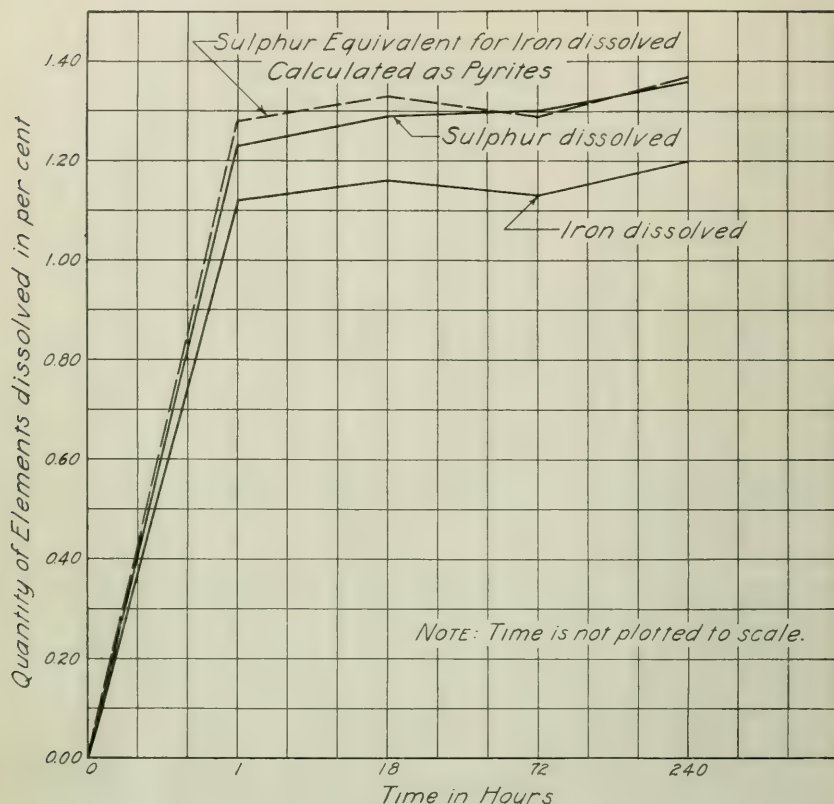


FIG. 3. CURVES SHOWING RESULTS OF THE EXTRACTION OF COAL NO. 7 WITH DILUTE NITRIC ACID

The data in Table 20 show that the quantitative extraction of the pyritic sulphur is best brought about by treatment at room temperature for several days. Any attempt to hasten the process by heat would result in the oxidation of some of the organic sulphur.

10. *The Determination and Identification of Humus Sulphur in Coal.*—The experiments on the phenol extraction of coal proved that a certain portion of sulphur existed in organic combination in the resinic type of material. The dilute hydrochloric acid extraction was the means of determining the sulphate sulphur, while dilute nitric acid quantitatively removed the pyritic sulphur from the coal. After the percentage compositions of these three known forms were added and their

sum was subtracted from the total sulphur, a quantity of sulphur was, however, shown to be still unaccounted for. Any possibility that this extra sulphur could be combined with the iron to form a sulphide higher than FeS_2 was eliminated by the nitric acid extraction experiments. It seemed necessary, therefore, to test for some other type of compound.

About five grams of coal No. 7 were extracted with concentrated nitric acid for twenty-four hours at room temperature. This treatment removed the pyritic and sulphate sulphur, but left the remainder in the residue, so that the latter could be studied conveniently by itself. Further treatment of the residue with nitric acid yielded no sulphur in the filtrate, nor did boiling with dilute nitric acid.

Guignet* and later Friswell† had observed the effect of alkalies on coal previously treated with nitric acid. Two portions of the nitric acid residue were accordingly placed in beakers, one being treated with 25 cc. of concentrated aqua ammonia and the other with a concentrated sodium peroxide solution. In both cases the thick dark brown solution described by Friswell was formed. The ammonia extract was diluted and filtered, the filtrate having a dark reddish brown color. Upon acidifying a portion of this filtrate with hydrochloric acid, a brown flocculent precipitate formed which was filtered off with the same difficulty that characterized the first filtration. The filtrate in this case was a very light yellow and contained no sulphur. This showed that the sulphur in the nitric acid residue must be present either in the ammonia insoluble substance, of which there was very little compared with the original residue, or in the flocculent brown precipitate. The qualitative analysis of this precipitate, sometimes referred to as "coal acid," showed large quantities of sulphur. An analysis of the small undissolved portion of the residue gave, furthermore, only a trace of sulphur. Anderson and Roberts‡ had found that this undissolved portion consisted of nearly 60 per cent organic matter very similar to the coal acid which would have gone into solution if it had not been occluded. This explanation could easily account for the trace of sulphur found. From this experiment, it was concluded that a knowledge of the unknown form of sulphur depended upon a study of the coal acid. The results of the sodium peroxide extraction were similar to those obtained with ammonia.

It was decided to find whether the unknown form of sulphur was

*See page 51.

†See page 51.

‡See page 52.

organic or inorganic in nature. The logical procedure was the study of the ash of the coal acid. Two grams of coal No. 7 were treated in the usual manner, the result being the formation of over 1.5 grams of ammonia soluble material. The ash content of this material was determined and when calculated on the basis of the original coal there was 0.35 per cent. The ash content of the original coal was 9.45 per cent; consequently only a very small part of the mineral matter was extracted by the ammonia. The ash was then treated with hydrofluoric and sulphuric acids to remove the silica. It was then heated to change the metals present to the oxides. This mixture of oxides was dissolved and analyzed for iron. The ash analyses by this method are:

Silica	0.10 per cent
Fe ₂ O ₃	0.05 per cent
Other oxides	0.20 per cent
Total ash	0.35 per cent

The unknown sulphur present in the ammonia extract amounted to about one per cent. It is inconceivable that this amount of sulphur could be combined in some inorganic compound while the mineral matter was present in so small an amount. The probability is, moreover, that if such a compound existed, it would not resist the action of concentrated nitric acid and then dissolve in ammonia. The conclusion is therefore drawn that this sulphur is of an organic nature, that it exists in the humus-like portion of coal described in the literature, and that its combination in such substances is extremely stable. Because of the nature of the body in which this form of sulphur occurs, it is referred to hereinafter as humus organic sulphur in order to differentiate it from the resinic organic sulphur.

As a means of verifying the methods just given, it was decided to determine the amounts of the various forms of sulphur present in certain coals, to add these together and to see how closely the total checked with the total sulphur of the coal as determined by sodium peroxide fusion. Extremely close checks were not expected, since the combined errors of five determinations entered into each comparison. Table 21 gives the average results obtained on five different coals, all that were studied in this connection.

The agreement of the two totals in each case is very satisfactory, when the long series of manipulations which were made to obtain the sum of the four sulphur forms is considered. The last three determina-

tions gave low results, probably due to the retention of some of the humus sulphur by the residue when the ammonia extraction was performed. Such retention was particularly strong with coal No. 8, which dissolved in the ammonia with great difficulty after the nitric acid treatment. The results obtained by the various extraction methods, however, determine the general character of all the sulphur of the coal.

Effort was made to secure more specific knowledge of the organic sulphur compounds present in coal, but with negative results. Smiles's test for sulphuric acids and sulfoxides was performed by treating some finely powdered coal with concentrated sulphuric acid and then by adding a drop of anisole. The same test was applied to some of the ammonia extract, but in neither case was the positive blue color obtained. The isatin test for thiophen also gave negative results. It is therefore probable that the nature of both the resinic and humus types of organic sulphur compounds in coal is very complex.

TABLE 21

ANALYSES OF DIFFERENT FORMS OF SULPHUR IN COALS AND COMPARISON
WITH TOTAL SULPHUR
(Values given in per cent)

Sample Number	4	5	6	7	8
Resinic Sulphur.....	0.34	0.16	0.77	0.50	0.10
Sulphate Sulphur.....	0.05	0.25	1.31	0.31	0.01
Pyritic Sulphur.....	0.85	0.31	2.06	1.36	0.29
Humus Sulphur.....	0.87	0.51	0.70	0.95	0.45
Total.....	2.11	1.23	4.84	3.12	0.85
Total S by Na ₂ O ₂ fusion.....	2.14	1.20	5.00	3.31	1.02
Difference between totals.....	0.03	0.03	0.16	0.19	0.17

III. CHANGES IN THE FORMS OF SULPHUR IN COAL

11. *The Effect of Standing upon the Forms of Sulphur in Coal.*—A noticeable feature in the present investigation was the rapid change of certain sulphur forms to sulphate. An extreme example was given in the coal known as No. 6 which had a sulphur content of 5 per cent. After the coal stood in a tightly stoppered Erlenmeyer flask for two years, the amount of sulphate sulphur had increased from less than 0.01 per cent to 1.31 per cent. Since the percentage of soluble iron had also greatly increased, it would seem that the pyrites oxidized in some manner. The following experiments were performed to establish this as a fact.

12. *The Oxidation of Sulphur in Coal.*—Some investigation was made to determine the most favorable conditions under which coal sulphur oxidation might occur. Five grams of coal No. 1 were placed in the bottom of an Erlenmeyer flask. A tube leading nearly to the bottom of the flask was connected to a U tube filled with thoroughly moistened glass wool. A slow current of air was passed through the U tube and thence into the flask, so that the finely powdered coal was at all times exposed to fresh moist air. The flask containing the coal was kept for eighteen hours in an electric oven which was regulated to maintain a constant temperature of 60 degrees. In order to compare the effect of moist and dry air another experiment was performed in which the U tube was filled with calcium chloride instead of the moist glass wool. The results obtained are given in Table 22.

TABLE 22
OXIDATION OF SULPHUR IN COAL BY MOIST AND DRY AIR¹

	Moist Air Per Cent	Dry Air Per Cent
Total sulphur in coal.....	2.68	
Sulphate sulphur in coal.....	0.045	
Sulphate sulphur in coal after oxidation by moist air.....	0.207	
Sulphur oxidized by moist air.....	0.162	
Sulphate sulphur in coal after oxidation by dry air.....		0.173
Sulphur oxidized by dry air.....		0.128

¹It is to be noted that the moist air caused a slightly larger amount of sulphate sulphur to be formed than did the dry air.

These results showed that a comparatively small portion of the coal sulphur was oxidized under the most favorable conditions of air supply, temperature, and fineness of coal. The only condition unfavorable to a very large amount of oxidation, on the other hand, was the short time of exposure. It seemed then that the oxidation of the sulphur depended upon the time of exposure of the coal or that some factor besides simple chemical oxidation entered into the change.

The experiment just described tends to show that the oxidation of the coal sulphur was not a simple reaction in which an excess of air would cause a proportionally greater change than that which would occur in a closed flask. This condition might be explained on the basis that certain anaerobic bacteria in the coal were causing the gradual oxidation of the coal sulphur in the absence of a free access of air. An attempt was made to determine the nature of the sulphur oxidation process by means of the following experiment.

Coal No. 7 was chosen since it was a comparatively fresh coal with a low sulphate content and a high percentage of pyrites. If bacteria were the cause of the change, they would be found in the largest quantity in a coal where a very decided sulphur oxidation had occurred. Coal No. 6 fulfilled this condition; so it was chosen as the inoculating agent. Four small flasks were fitted with rubber stoppers covered with tin foil, from which were suspended glass hooks to support some wet cotton so that the interior of the flasks would be continuously moist. In two of these flasks there were placed 5 grams of coal No. 7, finely powdered, in the other two 4 grams of coal No. 7. All four flasks were thoroughly sterilized in a steam autoclave.

After sterilization, one gram of coal No. 6 was added to each of the two 4-gram flasks. There were now two flasks containing sterile coal and two others containing sterile coal mixed with a smaller quantity of old heavily oxidized coal. The set of flasks was kept at a constant temperature of 37 degrees, and the contents were analyzed later for the hydrochloric-acid-soluble sulphur and iron. In order to find the increase in the sulphur of coal No. 6, two flasks containing one gram each were used as controls for the others. Analyses of the flask contents were made nineteen days after they were placed in the incubator room and another set of analyses was made eighty-eight days later.

From these data the increase in soluble sulphur and iron in all flasks was calculated. Since the sterile flask contained five grams of coal, this increase was multiplied by four-fifths to maintain a basis of four grams. The increase in the control flask was then added. If the proc-

ess were a simple chemical reaction, the result would be equal to the increase in the sterile flask, since this one was made up of four grams of sterile coal and one gram of coal No. 6. If, however, the action of bacteria entered into the change, a larger increase of soluble sulphur and iron would be expected in the flask where the sterile and the inoculated coals were in contact than would be found by adding the increases of the two separated flasks. Table 23 gives the results obtained.

TABLE 23
RELATIVE OXIDATION OF PYRITES IN STERILE AND INOCULATED COALS

COALS	19 Days	88 Days
Increase of soluble sulphur in 4 g. sterile coal No. 7.....	11.88 mg.	14.00 mg.
Increase of soluble sulphur in 1 g. coal No. 6.....	4.40 mg.	9.40 mg.
Calculated increase of sum of two preceding items.....	16.28 mg.	23.40 mg.
Actual increase of soluble sulphur by analysis.....	16.40 mg.	34.70 mg.
Increase of soluble iron in 4 g. sterile coal No. 7.....	14.05 mg.	15.00 mg.
Increase of soluble iron in 1 g. coal No. 6.....	5.55 mg.	10.40 mg.
Calculated increase of sum of two preceding items.....	19.60 mg.	25.40 mg.
Actual increase of soluble iron by analysis.....	19.70 mg.	38.00 mg.

At the end of nineteen days there was apparently nothing unusual in the relative oxidation of sulphur in the sterile and in the inoculated coal. At the end of eighty-eight days, however, the inoculated coal showed a decidedly greater increase than did the sterile coal, the only explanation for this being some bacteriological action or perhaps catalysis. Another interesting point to be noted is that the soluble iron shows a greater increase than the soluble sulphur in every case whether the coal is sterile or not. If only pyrites were being oxidized, there would be one and one-seventh times as much sulphur as there was iron, and if other sulphur forms were oxidized the ratio would be still larger. In actual practice, however, the opposite is true. The best explanation for this discrepancy would be that some of the sulphate formed was taken up by the organic matter of the coal.

13. *Changes in the Forms of Sulphur Effected by Coking.**—When coal is subjected to destructive distillation in the absence of air, the sulphur divides between the residue and the volatile matter. The ratio between the residual sulphur and the volatile sulphur varies between rather wide limits but is fairly constant for the same coal. The factors in the coal which control this ratio have not been deter-

*See Appendix III for a historical account of similar experiments.

mined except in a general manner. Certain coal constituents, entirely separate from the sulphur containing compounds, may have an effect on the percentage of sulphur retained in the coke, but in all probability the decisive factor in determining this percentage is the relative amount of the different sulphur forms present. Since the first part of this investigation furnished a good means for determining these sulphur forms, their effect on the proportion of residual sulphur in coking was studied. The types of sulphur compounds formed in the coke were investigated. An attempt was made to determine the relation between the quantities of these types formed in the coke and the quantities of the different types of sulphur in the coal. Since the forms of sulphur in coke are entirely different from those in coal, this latter problem involved an entirely new method of procedure.

To determine the amount of residual sulphur, a one-gram sample of the coal to be tested was coked in a small nickel crucible and heated for three and one-half minutes at the full heat of the Bunsen burner and then for another three and one-half minutes with a blast lamp. A tight-fitting nickel cover prevented oxidation of the coal. The coke was carefully removed and pulverized; then it was fused with sodium peroxide in the same manner as the coal had been in another part of this investigation. After the fusion had been dissolved in water, the sulphur was determined by means of the barium sulphate precipitation. Some of the coals used in this work were the original samples, while other experiments were made with samples which had previously been extracted with dilute hydrochloric acid to remove all the sulphur in the form of sulphate. Due allowance is made in Table 24 for this removal of the sulphate form in the amount of total sulphur.

TABLE 24

FORMS OF SULPHUR IN COAL AND RESIDUAL SULPHUR REMAINING AFTER COKING
(Values given in per cent)

SAMPLE NUMBER	5a	6a	7	7a	10	10a
Total sulphur.....	1.08	4.00	3.31	3.00	0.95	0.93
Sulphate sulphur.....	0.00	0.00	0.31	0.00	0.02	0.00
Pyritic sulphur.....	0.31	2.06	1.30	1.30	0.10	0.10
Resinic sulphur.....	0.16	0.77	0.50	0.50	0.13	0.13
Humus sulphur.....	0.61	1.17	1.20	1.20	0.70	0.70
Residual sulphur.....	0.34	1.46	1.37	1.09	0.45	0.38

The coals designated by a numeral and the letter "a" are those which were extracted with dilute hydrochloric acid before coking. It

is interesting to note the difference between the amounts of residual sulphur in these coals as compared with the amounts in the corresponding coals which had not been extracted. In coal No. 7 this difference corresponds almost to the sulphur which had been removed by the dilute hydrochloric acid. In coal No. 10, however, the difference is somewhat greater than that of the sulphate sulphur. A reasonable explanation for this difference would be that coal No. 10 contained calcite, which on heating changes to calcium oxide and on uniting with some of the hydrogen sulphide would ordinarily volatilize. In the coal previously extracted with acid, however, the calcite was removed; consequently the residual sulphur was less than that in the coal extracted with acid. Cursory study of the table will show the falsity of the theory that all the organic and one-half the inorganic sulphur are volatilized during coking. In order to determine in some degree the proportion of the various sulphur forms left in the coke, the following calculations were performed. Coals Nos. 6a, 7a, and 10a were chosen since these contained less of the sulphate form to complicate the calculations and since they would be free of calcite which might enter into a secondary reaction with some of the volatile sulphur as previously explained. There would then be three unknown quantities of residual sulphur to add to the total residual sulphur which was known. Then

Let X = fraction of pyritic sulphur left in coke

Y = fraction of resinic sulphur left in coke

Z = fraction of humus sulphur left in coke

For coal No. 10a, $.1X$ plus $.13Y$ plus $.7Z = .38$

For coal No. 6a, $2.06X$ plus $.77Y$ plus $1.17Z = 1.46$

For coal No. 7a, $1.30X$ plus $.5Y$ plus $1.20Z = 1.09$

Solving these equations simultaneously, the results are as follows:

Pyritic sulphur left in coke, 16 per cent

Resinic sulphur left in coke, 95 per cent

Humus sulphur left in coke, 34 per cent

These figures doubtless would not hold for every coal since other factors enter into the retention of the sulphur in the coke. They are interesting, however, inasmuch as they show that a large amount of the organic sulphur is retained.

The retention of so much organic sulphur led to some experiments on the nature of the sulphur compounds in the coke. Although Bradbury* had believed the large portion of the coke sulphur to be organic

*See page 62.

in nature, it was difficult to conceive any organic compound withstanding the high temperature of the coking process. A more reasonable explanation would be that secondary reactions caused the organic sulphur to change into some very stable inorganic form.

A method similar to that used by Bradbury was used to determine the nature of these sulphur compounds. The finely powdered coke was placed in a small flask which was arranged so that hydrogen could bubble through a liquid in the bottom and pass out the top into an absorption tower containing a moderately strong sodium peroxide solution. The coke from one gram of the original coal was used and over this about 40 cc. of dilute hydrochloric acid (one part HCl, sp. gr. 1.19, to one part water) were poured. A slow stream of hydrogen was then conducted through the apparatus for about one hour, and finally the solution in the flask was brought to boiling to insure the removal of the hydrogen sulphide.

By this method any sulphate sulphur in the coke would go into solution and the sulphide sulphur would be carried over in the stream of hydrogen as hydrogen sulphide which would be oxidized to sodium sulphate in the sodium peroxide tower. By barium sulphate precipitation both the sulphate and sulphide forms of sulphur in the coke could accordingly be determined. The residue of this extraction was then treated with concentrated nitric acid for two hours in order to extract any pyrites which might remain. The results of this experiment on coal No. 7 and a comparison of the forms of sulphur in coke with the forms of sulphur in the original coal are given in Table 25. The percentages of sulphur and iron in the coke are estimated

TABLE 25
FORMS OF SULPHUR IN COKE COMPARED WITH ORIGINAL COAL
(Values given in per cent)

	Coal No. 7	Coke from Coal No. 7
Total sulphur.....	3.31	1.37
Sulphate sulphur.....	0.31	0.00
Sulphide sulphur.....	0.00	0.30
Pyritic sulphur.....	1.30	0.00
Resinic sulphur.....	0.50	0.00
Humus sulphur.....	1.20	0.00
Unknown sulphur.....	0.00	1.07
Total iron.....	1.87	1.87
Soluble iron.....	0.41	1.04
Pyritic iron.....	1.13	0.00
Silicate iron.....	0.33	0.83

on the basis of the weight of the original coal used, so that a direct comparison may be made with the coal.

The results show that the structure of the larger part of the sulphur in the coke is as yet undetermined. The concentrated nitric acid treatment removed only 0.07 per cent. so that the compounds in which sulphur is present must be very stable. The possibility of a carbon-silicon-sulphur compound presented itself, but all such compounds in the literature decompose in the presence of water or of hydrofluoric acid, releasing hydrogen sulphide. No hydrogen sulphide could be detected even when the finely powdered residue of this extraction was boiled with hydrofluoric acid. It therefore seems not to be an iron-sulphur compound, nor is it a silicon-sulphur compound. According to present data it seems to be a carbon-sulphur compound, the nature of which is as yet undetermined.

After the finely powdered coke had been boiled with dilute hydrochloric acid to release the sulphide sulphur as hydrogen sulphide, a quantity of fine aluminum turnings and some more dilute hydrochloric acid were added to the residue and the mixture again heated. Under these conditions a large amount of hydrogen sulphide was removed. This action of nascent hydrogen on the coke would also indicate the organic or carbon-sulphur character of this portion of the coke sulphur.

There are other indications of the theory that certain carbon compounds persist through the high temperature condition to which coal is subjected in the coking process. The treatment of red coke with water vapor, for example, releases a large amount of nitrogen as NH_3 which was held in some chemical combination with the carbon. In addition to ammonia, hydrogen sulphide is released from the coke by the same treatment. During the coking process, hydrogen compounds persist as high as and beyond a temperature of 1000 degrees Centigrade. These well known facts show that nitrogen, sulphur, and hydrogen may remain in organic combination at very high temperatures.

It has been previously stated that the coal material extracted by phenol consists entirely of organic matter of a resinic nature. In order to investigate the sulphur distribution during coking in this type of material, one gram of the extracted substance from coal No. 7 was coked under standard conditions. It was found that 50 per cent of this form of organic sulphur was retained in the coke; thus definite proof was obtained that a portion of the coke sulphur was organic in character and source.

Some of the indicated changes shown in Table 25 are worthy of

comment. The sulphate sulphur disappears entirely because of the reducing influence of the red hot carbon, but it does not change to the sulphide form, as will be shown later. It probably goes over to the unknown form of sulphur, since the residual sulphur is higher if the sulphate is not extracted with hydrochloric acid before coking. The source of the sulphide sulphur will be explained later. The pyritic sulphur is entirely decomposed during the coking process.

Both organic forms of sulphur in the coal change from their original form, as shown by the fact that phenol has no effect on the coke and that ammonia will not dissolve the nitric acid residue, these being characteristic properties of the two sulphur forms in the coal.

Some of the changes in the forms of iron during the coking process indicate that they are important changes. The acid soluble iron increases greatly. This change would be expected if all the pyrites decomposed. The decomposition of the pyrites also leads to a decided increase in the content of iron silicate.

The source of the sulphide sulphur in the coke was investigated. Four one-gram samples of coal No. 7 were extracted with dilute hydrochloric acid and two of these were further extracted with phenol. The residues were coked and the sulphide sulphur was determined as in the previous experiment. The original coal, as given in Table 25, yielded 0.30 per cent sulphide sulphur in the coke. After hydrochloric acid extraction of the coal, the coke still contained 0.31 per cent, and even after further extraction with phenol 0.27 per cent sulphide sulphur. These results indicate that the origin of the sulphide sulphur of the coke was not in the sulphate or resinic sulphur. In all probability the origin is in the iron pyrites.

IV. SUMMARIZED STATEMENT OF ANALYTICAL METHODS

To determine the kinds of sulphur in coal, methods were developed for the quantitative analysis of each form of sulphur. The methods, for greater convenience, are brought together as follows:

(1) The sulphate sulphur is determined by extraction of the coal with dilute hydrochloric acid. For this purpose 5 grams of the coal ground to 100 mesh is extracted with 300 cc. of 3 per cent hydrochloric acid for 40 hours. The extraction is carried out in a beaker placed on a steam bath with a temperature of 60 degrees Centigrade maintained. After the extraction is filtered, the sulphate sulphur may be precipitated from the filtrate by means of barium chloride.

(2) The pyritic sulphur is determined by extraction of the coal with dilute nitric acid, after a preliminary extraction with dilute hydrochloric acid to remove the sulphate form. If the sulphate content is low, the nitric acid extraction may be performed on the original coal, allowance being made for the sulphate form by subtraction. For this purpose it is best to use one gram of the finely powdered coal covered with 80 cc. of dilute nitric acid (one part nitric acid, sp. gr. 1.42, to three parts water; sp. gr. of the mixture is 1.12). The mixture is allowed to stand at room temperature for at least four days. It is then filtered, the nitric acid driven off by evaporation to dryness and the residue taken up in some water and hydrochloric acid. In addition to determining the sulphur in this solution, the iron may also be estimated since the iron-sulphur ratio will serve as a check on the selective solution of pyrites.

(3) The resinic sulphur is determined by extraction of the coal with phenol. One-half gram of the finely powdered coal is placed in a flask fitted with an air condenser. Twenty-five cubic centimeters of phenol are poured over the coal and the extraction is carried out for 20 hours at a temperature of 140 degrees Centigrade. The best means for maintaining this temperature is a regulated electric oven. The contents of the flask are then filtered through a Gooch crucible, and rinsed with alcohol and ether. The residue in the crucible is mixed with sodium peroxide and fused. The sulphur determination on this

residue gives that portion of the sulphur not extracted by the phenol, and by subtracting this amount from the total sulphur, the resinic sulphur is determined.

(4) The humus sulphur is determined by the difference between the sum of the other three forms and the total sulphur in the coal. A direct determination may be made by extraction of the coal with ammonium hydroxide, after a preliminary treatment with concentrated nitric acid. This method is applicable only to the softer coals, the structures of which are fundamentally changed by the nitric acid treatment. For this method, one gram of the finely powdered coal is treated with 15 cc. of concentrated nitric acid for a short time (about one-half hour). This mixture is then diluted, filtered, and washed. The filter paper which contains the residue is put into 25 cc. of concentrated ammonia (sp. gr. 0.90), and allowed to stand for several hours when it is then diluted and filtered through a large fluted filter. The filtrate is evaporated to dryness and the dry residue gathered and fused with sodium peroxide. The sulphur in this fusion represents the humus sulphur.

APPENDIX I

THE CONSTITUTION OF COAL

The changes in the process of coal formation indicate the composition of coal, but no definite conclusions may be drawn since the chemical changes involved vary under different conditions and are obscure in all cases.

It is conceded by practically every one that coal had its origin in vast beds of vegetable matter, supplemented in most cases by animal remains. Several reasons may be advanced as proof of the vegetable origin of coal, the most important of which is the frequent occurrence of plant outlines on coal surfaces. Morphological proofs of the presence of animal residues are, however, not so plentiful, but outlines of the skeletons of fishes are often found, and they indicate the presence of water during the early stages of coal formation. Another good indication of animal remains in the coal is found by a comparison of its nitrogen content with that of pure vegetable fossils found in the same general locality. In such cases the coal contains several times as much nitrogen as the vegetable remains, this fact undoubtedly showing the presence of animal matter in the coal.*

The beds of vegetable matter have accumulated during long periods of time and complete oxidation of the organic matter is prevented by compact layers of earthy material. The chemical composition of the original plant material was similar to that of cellulose, with varying amounts of mineral matter and a large amount of water present. This vegetable sphagnum becomes peat by a process of slow decay. The chemical changes in this transformation are typical of a kind of bacterial cellulose decomposition, the products of which are the so-called humus substances, such as humic, ulmic, crenic, and apocrenic acids. None of these products is a definite chemical compound since each product represents merely a type of substance. As peat is acidic in character, nearly all of it will dissolve in an alkaline solution. Underground waters carry lime and iron salts in solution to the peat and cause the formation of insoluble calcium and iron salts of the acids. Although calcium and iron are found in the ash of peat, the calcium rarely exists as the carbonate, as might be expected.† The change from vegetable

*Clarke, F. W., "The Data of Geochemistry," p. 654, 1908.

†Berichte der Deutschen Chemischen Gesellschaft, Vol. 15, p. 2961, 1882.

matter to peat is accompanied by loss of both water and oxygen, so that the net result is a gain in the carbon content and a loss of both hydrogen and oxygen. Each step in the process of change from peat to anthracite coal involves, moreover, the same result—a continuous increase in the percentage of carbon, a decrease in the percentage of hydrogen and a decrease of oxygen until nearly all the oxygen has disappeared.

Lignites form the connecting link between the distinctly vegetable peat and the rock-like bituminous coal. These are soft deposits and generally light brown. They contain organic sulphur as well as pyrites or marcasite and sulphates such as gypsum.*

The changes from lignites to bituminous coal and then to anthracite coal give no suggestion of the chemical composition of coal, except perhaps its tendency to approach a hydrocarbon. The earlier chemical changes are, according to White,† largely bio-chemical, while the later changes are more distinctly dynamo-chemical.

Nearly all the foregoing discussion refers to the carbon, hydrogen, and oxygen in the coal. The methods of formation of the nitrogen and sulphur compounds depend upon the combination of these elements in the coal. A large part of the nitrogen of the coal comes from the remains of animals, and since the remainder comes from the plant substance, it must exist as organic amino nitrogen, unless there have been nitrifying bacteria present which cause oxidation.

The sulphur of the coal may come from two entirely different sources. The original plant and animal substances from which the coal was formed undoubtedly contained organic sulphur. Whether this organic sulphur changes during the coal making process is not known, but there is evidence that it may furnish the sulphur for the pyrites and marcasite of the coal. Since iron and calcium are precipitated from ground waters by the humus acids of the peat as it undergoes change, hydrogen sulphide waters percolating through the coal substance would change the iron to the sulphide and thence to pyrites or marcasite. If sulphur is found in the form of sulphate in fresh coal, it is found only in small percentages.

Where aerated water has the chance to come in contact with pyrites, however, a very slow oxidation occurs. Winchell‡ states that he made tests with aerated water acting on pyrites. At the end of one month,

*Dana, James D., "The System of Mineralogy," 6th ed., p. 1010, 1895.

†Economic Geology, Vol. 3, p. 293, 1908.

‡Economic Geology, Vol. 2, p. 290, 1907.

he found that neither iron nor sulphur had gone into solution. At the end of ten months, 0.2 g. of pyrites had been oxidized and there were in the solution 27.7 mg. of ferric sulphate and 5.7 mg. of sulphuric acid per liter with traces of ferrous salts and sulphur dioxide. These tests show that it is possible for comparatively large quantities of sulphate to be formed in the coal, provided the flow of the aerated water does not leach out the compounds so fast as they are formed. Any sulphate formed would have the tendency to change to calcium sulphate or another sulphate not so soluble as the ferric salt.

It has also been found, according to Stokes,* that alkaline waters decompose pyrites and marcasite to ferric oxide. The sulphur decomposes in the form of alkali sulphides and thio-sulphates. It is stated that oxygen is not necessary for this action to occur. These examples suggest that pyrites may undergo secondary changes while in the underground coal.

There is a third source possible for the sulphur in coal besides the original vegetable matter and percolating waters. While the coal is still in the process of formation, it is very likely to be mixed mechanically with detritus, which may account for not only a large part of the ash of coal but also for some of the inorganic sulphur.†

A general method used to determine the constitution of coal is that of destructive distillation. This method has been studied more thoroughly than the others because of the commercial importance of coking processes and gas manufacture; yet it is the poorest from the standpoint of determining the real nature of the coal substance. It is now a well proved fact that all the products of distillation of coal do not come from the coal by simple distillation, but that every one of them is the result of the decomposition of more complex compounds. A discussion of the destructive distillation must be limited to only those facts which tend to show the nature of the coal substance.

The products resulting from the destructive distillation of coal consist of gaseous, liquid, and solid condensate and a residue which is largely carbon mixed with the ash of the coal. Among the volatile products are ammonia, carbon dioxide, hydrogen sulphide, hydrogen, methane, carbon monoxide, nitrogen, acetylene, ethylene, other hydrocarbons, pyridin, phenol, benzene, toluene, xylene, naphthalene, anthracene, phenanthrene, cresol, and a great variety of other aromatic compounds. Because of the predominant presence of ring hydro-

*Economic Geology, Vol. 2, p. 14, 1907.

†Hinrichsen, F. W., and Taczak, S., "Die Chemie der Kohle," p. 124, 1916.

carbons and their derivatives, it has been supposed that the original coal consisted of ring-like compounds.

R. Meyer* has an interesting theory concerning coal structure. He believes the main part of the coal to be composed of compounds which are merely polymers of acetylene and which change very readily into acetylene on heating. The nitrogen exists in such a form that it will come out as ammonia or hydrocyanic acid. When the coal is being distilled, these primary decomposition products unite in various combinations to give the ordinary distillation products. Meyer performed some experiments to substantiate this theory. By passing acetylene, mixed sometimes with ammonia or hydrocyanic acid, through a heated tube, he obtained a variety of products, among which were benzene, toluene, diphenyl, styrol, inden, naphthalene, anthracene, phenanthrene, pyrene, fluorene, acenaphten, chrysene, hexylene, pyridin, anilin, carbazol, and benzonitrile. All these products, with the exception of the hexylene, have been separated from coal tar. His theory of coal composition is undoubtedly at least partially correct, but whether it applies to all the organic compounds of the coal is doubtful from such evidence.

The largest part of the sulphur of coal comes off on distillation as hydrogen sulphide, but there are also thiophen compounds in the tarry distillate. The presence of hydrogen sulphide indicates not only the sulphur lost by the pyrites on heating, but may show the presence in the coal of complex organic sulphur compounds of a protein nature. From Meyer's theory the thiophen ring compounds could be formed by a secondary reaction between acetylene and hydrogen sulphide; therefore the presence of thiophen or its derivatives could hardly be considered as proof of the existence in the coal of cyclic organic sulphur compounds.

Another method for determining the composition of coal is by means of selective solvents. This is by far the best of the three methods. Any constituent obtained will be in the condition in which it existed in the coal or because of the simplicity of the extraction the original substance may be easily deduced. This method of analyzing the coal structure is increasing in use.†

The solubility of the humus acids of peat in alkalies has been previously mentioned. F. G. Kaufmann‡ has regarded peat as a mixture of

*Berichte der Deutschen Chemischen Gesellschaft, Vol. 45, p. 1609; Vol. 46, p. 3183, 1913.

†Journal of the Society of Chemical Industry, Vol. 36, p. 176, 1917.

‡Verhandlungen der Kaiserlich-Königlichen Geologischen Reichsanstalt, Vol. 15, p. 283, 1885.

two substances, dopplerite, the portion soluble in caustic alkali solutions* and another substance consisting of partly decomposed vegetable matter.

By the solvent method, peat has also been found to contain resinous substances as high as 3.26 per cent of the content of the peat. The resins are extracted by using hot ether or alcohol as solvents.†

Resinoids and fossil hydrocarbons are abundant in lignites. The fossil hydrocarbons are generally visible as definite masses. The resinoids are very often disseminated throughout the coal; consequently solvents must be used as extraction agents. Benzene and other organic solvents will extract the resins, which have been found to be indefinite in composition. Watson Smith‡ states that he obtained 9.5 per cent of extractive matter by the action of benzene on a Japanese lignite.

Humus compounds are present in lignites, but not to so great an extent as in peat; hence xyloid lignite is found to dissolve in caustic alkali to an extent somewhat less than peat, and very little solvent action can be obtained with the more compact lignites.¶ Bituminous and anthracite coals are not dissolved at all by alkaline solutions; so there must be a gradual destruction of the humus compounds during the coal evolution process. At times humus bodies are found in large percentages. Among the "paper coals" of Russia are found deposits of humic matter soluble in ammonia. § In Bohemian brown coal von John found a humus acid, with the approximate formula $C_{36}H_{46}O_{25}$, soluble in ammonia or sodium carbonate.** A fossil humus from a Tertiary deposit near Cassel, Germany, furnishes the pigment known as Cassel brown.

Fremy†† states that lignites are soluble in alkaline hypochlorites, while the older coals are not. Nitric acid attacks lignites very vigorously, and causes the formation of a yellow resinous body which will dissolve in an excess of the nitric acid or in an alkaline solution. This property of the lignites is very important from the standpoint of coal

*Dana, James D., "The System of Mineralogy," 6th ed., p. 1014, 1895; Claessen, C., "Ueber Dopplerit," *Chemiker-Zeitung*, Vol. 22, p. 523, 1898; Alexejew, W., "Ueber Elaterit und Dopplerit," *Zeitschrift für Krystallographie und Mineralogie*, Vol. 20, p. 187, 1892.

†Jacobsen, Oscar, *Annalen der Chemie und Pharmacie*, Vol. 157, p. 240, 1871; Mulder, idem, Vol. 32, p. 305, 1839.

‡*Journal of the Society of Chemical Industry*, Vol. 10, p. 975, 1891.

¶Fremy, *Comptes Rendus de l'Académie des Sciences*, Vol. 52, p. 114, 1861.

§Zeiller, M. R., "Note sur la compression de quelques combustibles fossiles," *Bulletin de la Société Géologique de France*, Vol. 12, series 3, p. 680, 1884.

***Verhandlungen der Kaiserlich-Königlichen Geologischen Reichsanstalt*, p. 64, 1891.

††*Comptes Rendus de l'Académie des Sciences*, Vol. 52, p. 114, 1861.

constitution and has been used with marked success in the present research to determine several unknowns. This treatment of coal with nitric acid cannot be regarded as a simple solution method; yet it is included with this method because of the close analogy existing between the two.

E. Guignet* was the first investigator to study in much detail the action of nitric acid upon coal, and he concluded that the products formed were similar to the nitrocelluloses. This work was followed by that of R. J. Friswell,† who fails to acknowledge the previous work of Guignet on this subject but describes the phenomenon accurately, as follows:

"If bituminous coal in fine powder be covered with rather more than double its weight of 49 per cent nitric acid, the mass rapidly becomes warm, and dense red fumes are given off. If 90 g. of coal and 200 cc. of the acid are taken, the action is extremely brisk, and the frothing so violent that a 2000 cc. flask is requisite to contain the mass. In about 30 minutes the action slackens, and heat being now applied, the action is kept going at such a rate that a brisk evolution of gas continues; the solution is gradually raised to the boiling point and there maintained, the total time occupied being about 6 hours. The whole is now diluted, poured into a filter, and well washed. The filtrate consists of dilute nitric acid, with salts of calcium, iron, etc., in solution. The black residue on the filter is apparently unchanged coal. When washed free from acid, the residue is introduced into a flask and boiled with a dilute solution of sodium carbonate: nearly the whole dissolves, carbonic anhydride being briskly evolved. The resulting deep black-brown colored liquid filters with great difficulty, but by careful treatment with water in deep vessels the insoluble matter from the 90 g. of coal was found to be 12.5 g., consisting of coarse particles of coal, sand, etc."

He proceeds to say that with some coals practically all the organic matter of the coal could be taken into solution by nitric acid, particularly if the coal were very finely divided. If the filtered solution is acidified with hydrochloric acid, a "bulky, deep brown-black, flocculent precipitate" is formed, which is insoluble in water containing traces of mineral salts or acids but which is fairly soluble in boiling distilled water from which it separates again on cooling.

This "coal acid," as it is sometimes called, when dried at 100 degrees Centigrade forms shining black masses with conchoidal fracture. When

*Idem, Vol. 88, p. 590, 1879.

†Proceedings of the Chemical Society, Vol. 8, p. 9, 1892.

heated on platinum foil, the substance swells into a brilliant black mass, resembling very much in this respect a nitro compound of high carbon ratio. To investigate this resemblance, Friswell attempted reduction by means of zinc dust and caustic soda and also by sodium amalgam and acid reducing mixtures, but in no case was there formed a nitro reduction product. Dry distillation with zinc dust drove off the nitrogen in the form of ammonia, pyridin, and cyanides.

The coal acid seemed to be similar to the humus acids of peat, but it is different in several respects. In the first place the coal acid is not hygroscopic as humus acids have been found to be. After the coal acid is dried, it may again be dissolved, but the humic acid will not dissolve. The coal acid, furthermore, does not yield acetic acid on dry distillation. Some of the humus acids yield ammonia when boiled with alkalis, differing in this respect from coal acid as might be expected from evidence that it is a nitro compound.

This work was followed by that of Anderson and Roberts,* who investigated particularly the ultimate composition of the coal acid and its relationship to the type of coal. They found that the substance consisted of carbon, hydrogen, oxygen, nitrogen, and sulphur together with a small quantity of ash, mostly iron oxide. For the same type of coal they found the composition almost constant. After the coal was treated with nitric acid and then with ammonia, only a very slight residue remained. This residue was found to consist of 36 per cent mineral matter and occluded organic matter which was very similar to the coal acid and which would probably have gone into solution had it not been so intimately mixed with the other residual substances. They assert that the presence of sulphur in the coal acid is the first proof of the existence of organic sulphur in the coal.

In order to get some more data on the nature of the coal acid, Anderson and Roberts heated samples of Ell coal for four hours in a stream of carbon dioxide at 300-315 degrees Centigrade. At the end of this time the dry Ell coal was found to have lost about 9.5 per cent of its weight. The residue was treated in the usual manner to obtain the coal acid, and an ultimate analysis was then made. After the analysis of this substance was compared with that of the coal acid from the original coal, the two were found to be practically identical in ultimate composition; consequently the conclusion is drawn that the "nitrogenous molecule" of the coal is stable at that temperature. Other experiments and particularly portions of the present research show that this organic

*Journal of the Society of Chemical Industry, Vol. 17, p. 1013, 1898.

component, comprising the larger part of the coal matter, is unusually stable, not only to heat, but to many strong chemical reagents.

More work was done on coal solvents by a committee of the British Association,* but this work was incomplete. In addition to other solvents, the action of a mixture of hydrochloric acid and potassium chlorate was tried on coals. This oxidizing reagent seemed to differ in its mode of action from nitric acid in that the final product appeared to be a chlorinated substance.

Considerable investigation has been undertaken by E. Donath on the reaction of nitric acid with coal.† He finds that dilute nitric acid will react vigorously with lignite, but has no action on bituminous coal. He concludes, therefore, that the one is not a transformation product of the other, but that they have entirely different origins. This conclusion, although partially true, is probably too sweeping in character.‡

Franz Fisher in recent years has tested the action of ozone on coal.§ He finds that after ozone has been allowed to act on finely powdered coal, the coal is in such a condition that as much as 92 per cent of it may be soluble in water. The substance appears to be acidic in character, and is probably intimately related to the product resulting from the action of nitric acid on coal.

The solution methods so far given have been particularly of a destructive nature to the coal substance. Other investigations have been made with simple solvents, which have presumably extracted the unchanged coal constituents. The first reference to work of this kind is in a report to the Commissioners of the 1851 Exhibition by Doctor Smythe of Göttingen. He tried the following solvents, given in the order of their extractive ability, on a brown Cologne coal, benzene, chloroform, alcohol, ethyl ether, petroleum ether, and acetone.¶

Reinsch** in 1885 tried the action of alkaline solutions on the raw coals. He believed coals to be composed of two characteristic substances, which could be distinguished by this reaction.

*Annual Report, British Association, 1894, p. 246; 1896, p. 340.

†Chemiker-Zeitung, Vol. 29, p. 1027, 1905; Zeitschrift für anorganische Chemie, 1906, p. 557; Oesterreichische Zeitschrift für Berg-und Hüttenwesen, Vol. 51, p. 310, 1903; Chemiker-Zeitung, Vol. 28, pp. 180, 953, 1904.

‡Clarke, F. W., "The Data of Geochemistry," p. 653, 1908.

¶Berichte der Deutschen Chemischen Gesellschaft, Vol. 49, p. 1472, 1916; Engineering, Vol. 103, p. 296, 1917.

§Bedson, P. Phillips, "Notes on the Proximate Constituents of Coal," Journal of the Society of Chemical Industry, Vol. 27, p. 149, 1908.

**Dingler's Polytechnisches Journal, Vol. 256, p. 224, 1885; Journal of the Chemical Society, Abstracts, Vol. 48, p. 876, 1885.

In 1901 Baker investigated the action of pyridin on coals.* He found that only a very small percentage of the anthracite coal was soluble, while in some cases as much as 20.4 per cent of bituminous coals went into solution. The solutions were brown colored and sometimes fluorescent. No relationship could be obtained in the proportion of the elements in the coal, the residue, and the extract. Anderson and Henderson also did some work on the pyridin solution of coal.† This investigation was undertaken with three types of coal, Japan, Bengal, and Scotch, and the extracts from all seemed to be similar in properties and chemical constitution.

A similar research was carried out by Donath on a German coal.‡ By treating a coal with pyridin, he obtained a brownish-red solution, which gave a flocculent brown precipitate on addition of water or petroleum ether.

Bedson in 1908 performed a number of experiments with the pyridin extraction of coal.§ He found that gas coals yielding from 64 to 66 per cent of coke gave from 24 to 35 per cent of pyridin soluble material. Bedson thought that the pyridin soluble substances had some relationship to the volatile matter, but this supposition seemed to be disputed by the work of Dennstedt, Hassler, and Bünz,¶ who found that coals yielding from 62 to 87 per cent of coke (on an ash free basis) gave a pyridin extract which had only from 0.6 to 18 per cent of soluble matter. Wornast tried out the relationships on different gas coals.** A Loth-ringer gas coal yielding 50 per cent coke gave an extract of 12 per cent, while a Westphalian gas coal yielding 62 per cent coke gave 29 per cent. Rau concludes from results of this sort that in general more recent coals give a smaller extract than gas coals, that the maximum extract is reached at a coke yield of about 65 per cent, and that the amount of extract again decreases until anthracite coals give almost nothing.

Lewes investigated the action of pyridin on coal, particularly with reference to its effect on the coking properties.†† He states that the coking power of a coal is mostly or entirely removed by the pyridin

*Transactions, North of England Institute of Mining and Mechanical Engineers, Vol. 50, (2), p. 23, 1901; Journal of the Society of Chemical Industry, Vol. 20, p. 789, 1901.

†Journal of the Society of Chemical Industry, Vol. 21, p. 242, 1902.

‡Zeitschrift für angewandte Chemie, Vol. 19, p. 657, 1906.

§Journal of the Society of Chemical Industry, Vol. 27, p. 147, 1908; Journal für Gasbeleuchtung, Vol. 51, p. 627, 1908.

¶Zeitschrift für angewandte Chemie, Vol. 21, p. 1825, 1908.

**Rau, O., "Ueber die Fortschritte in der Gewinnung der Nebenprodukte beim Kokereibetriebe," Stahl und Eisen, Vol. 30, p. 1236, 1910.

††Progressive Age, Vol. 29, p. 1030, 1911.

extraction, and ascribes this fact to the removal of resinic bodies necessary to the coking of a coal. He explains the retention of the coking properties by some coals even after pyridin extraction by assuming the presence of a resinic body not soluble in the pyridin. Lewes, in addition to previous investigators, had noticed that some coals yielded a higher percentage of volatile matter after rather than before extraction, and he believed that this phenomenon was due to the retention of some of the pyridin. His conclusions on the nature of the resinic bodies were that they were of two kinds, "the one easily oxidizable, soluble in pyridin and saponifiable by alkalies, and which on weathering is oxidized into a humus body with the evolution of water and carbon dioxide, and is responsible for the heating of coal in storage; the other class non-oxidizable, not saponified by alkalies, and forming with pyridin a compound insoluble in excess of the reagent, and this class may be the hydrocarbons from decomposed resins, as the residue in which they are present yields rich liquid hydrocarbons, as tar and pitch, but not rich in gas."

Wahl in 1912 investigated the action of certain coals toward pyridin.* He found the volatile matter in the coal higher than that of the residue after pyridin extraction. The coke produced from the residue was more compact than that of the original coal.

In 1912, Frazer and Hoffman published the results of their researches on the action of phenol on coal.† Before deciding on the use of phenol as an extractive agent, they tried various other solvents, but they found that phenol, pyridin, and anilin gave the best results. A non-coking bituminous coal from Franklin County, Illinois, was selected for the investigation. A large quantity was finely ground and extracted with phenol at 140 degrees Centigrade for about 10 hours, and then the mixture was filtered. The extract was a dark red and was concentrated under diminished pressure to separate most of the phenol; then the remainder of the phenol was washed out by means of sodium hydroxide. The residue from the phenol extraction was not studied any further, but the phenol soluble material was treated with a 10 per cent sodium hydroxide solution. Both the soluble portions of this sodium hydroxide treatment were extracted with ether. In both cases, the ether insoluble compounds showed not only carbon, hydrogen, and oxygen, but also sulphur and nitrogen, while the ether soluble compounds showed only the first three. Each of the four mixtures was further separated by

*Comptes Rendus de l'Académie des Sciences, Vol. 154, p. 1094, 1912.

†"The Constituents of Coal Soluble in Phenol." U. S. Bureau of Mines, Technical Paper 5, 1912

means of other solvents and fractional distillation in certain cases, until about thirty different substances had been obtained and analyzed. Frazer and Hoffman assumed these substances to be the same as in the coal, and thought the evidence was fairly conclusive that these substances nearly approached being pure compounds.

In 1913, Pictet and Ramseyer extracted coal with benzene. The oil so obtained was fractionated by distillation and the different fractions studied. From this investigation, they believe coal to contain polymerized hydroaromatic hydrocarbons.*

From their work on the phenol extraction of coal in 1913, Clark and Wheeler believed coal to be composed of two types of substances.† They called them the "hydrogen yielding" and the paraffin yielding, respectively. The distinction refers principally to the ease of decomposition, since it has been found that there is a large amount of hydrogen released between 750 and 800 degrees. They considered the pyridin insoluble substance to be a degradation product of cellulose. They were somewhat doubtful whether the pyridin extract consisted entirely of resinous material, but when the pyridin soluble substance was extracted with chloroform, nearly pure resinous material was dissolved. This work of Clark and Wheeler as well as that of White‡ and Jeffrey¶ has fairly definitely established the hypothesis of the two general types of bodies in coal, first the degradation products of cellulose, and secondly the resinic type of bodies.

In conformity with this idea, Parr and Hadley studied the phenol extraction of coal, with particular reference to the properties of both the extract and the insoluble residue.§ The temperature in all these experiments was above 110 degrees Centigrade. The results of this work may briefly be summarized as follows. The amount of soluble material varied in different types of coal, for example, Vermilion County coals yielded from 35 to 40 per cent of soluble matter, Madison and Montgomery county coals from 30 to 35 per cent, and Williamson County coals only from 20 to 30 per cent. All these figures are on an ash and moisture free basis. The residue from the extraction would not coke; thus the coking constituent was shown to be in the phenol extract. Both residue and extracted material oxidized at room tem-

*Archives des Sciences Physiques et Naturelles, Vol. 34, series 4, p. 234, 1912; Chemical Abstracts, Vol. 7, p. 1496, 1913.

†Transactions, Journal of the Chemical Society, Vol. 103, p. 1704, 1913.

‡U. S. Geological Survey, Professional Paper 85-E, 1914.

¶Proceedings of the American Academy of Arts and Sciences, Vol. 46, p. 273, 1910.

§"The Analysis of Coal with Phenol as a Solvent." Univ. of Ill. Eng. Exp. Sta., Bul. 76, 1914.

perature and more rapidly at 100 degrees Centigrade. The extract contained more volatile matter than did the residue, although the ultimate composition was about the same in both cases, and the gases released have about the same composition. Some other facts concerning the oxidation of coal were established by this process.

The method of extraction which Parr and Hadley used was continuous in its action, that is, fresh solvent was at all times acting on the finely powdered coal. The coal was contained in an extraction thimble supported in a Kjeldahl flask, in the bottom of which was the boiling phenol. The vaporized phenol was condensed at the top of the flask by a boiling toluene condenser, so that the phenol would drop on the coal at a temperature of 110 degrees Centigrade or more. Carbon dioxide was passed through the extraction flask to prevent oxidation by the air.

Regarding the distribution of sulphur between the residue and extract, the following statement is made:

"It is to be noted that the percentage of sulphur in the residue is high. This is to be accounted for by the fact that the residue contained practically all of the ash that was present in the coal. That there was some sulphur in the extract was taken to indicate that a part of the sulphur in the coal was present in the organic form."*

*Parr, S. W., and Hadley, H. F., "The Analysis of Coal with Phenol as a Solvent." Univ. of Ill., Eng. Exp. Sta., Bul. 76, p. 27, 1914.

APPENDIX II

THE DEVELOPMENT OF A METHOD FOR ANALYZING THE DIFFERENT FORMS OF SULPHUR IN COAL BY OTHER INVESTIGATORS

Many methods have been devised for the determination of the total sulphur in coal, all of them depending on the use of an oxidizing reaction sufficiently strong to convert every form of sulphur in the coal into soluble sulphate. The practical importance of total sulphur determinations has long been recognized, because in the combustion of high sulphur coals large quantities of corrosive gases are released and because in coking processes a large percentage of the sulphur is retained in the coke.

Any relationship, however, between the amount of total sulphur and the amount of sulphur in flue gases or coke has never been found, because the sulphur does not exist in only one form, but in several entirely different combinations. Any method for analyzing the separate forms of sulphur in coal would help to solve these problems. Engineers are now realizing the importance of such a method, since data obtained from such analyses would give information necessary in deriving the correct heating value of the coal, the amount and character of corrosive gases, and the distribution of sulphur in coking, while a total sulphur analysis gives these data in only a very general manner.* Some method for obtaining these data would be of scientific value, since it would be one more step toward the determination of coal constitution.

W. A. Bradbury in 1878 indicated that sulphur exists in coal in organic combination.† The first method proposed to determine this organic sulphur separately from the inorganic was that of T. M. Drown.‡ He treated the finely powdered coal with a sodium hydroxide solution of 1.25 sp. gr., which had previously been saturated with bromine. After this sodium hypobromite treatment, the solution was acidified with hydrochloric acid, and then, if necessary, the hypobromite treatment repeated on the residue. The solution was evaporated to get rid of silica, taken up in hydrochloric acid and water, and the sulphate precipitated. Drown claims that only the sulphur existing as pyrites

*Martineau, Albert, "The Effect of Sulphur on the Value of Coal," *Electrical World*, Vol. 69 p. 698, 1917.

†*Chemical News*, Vol. 38, p. 147, 1878.

‡*Ibid*, Vol. 43, p. 89, 1881.

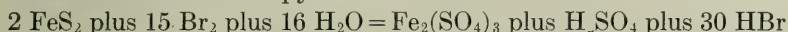
and sulphate are taken into solution by this method; therefore the organic sulphur is left in the residue.

The same investigator also tried the effect of hydrochloric acid and potassium chlorate on the same coals. By this method, the coals having a small percentage of pyrites gave the same results as with the other method, but those containing much pyrites gave higher results. With the hypobromite method very good checks were obtained, but Drown could offer no proof that only the inorganic sulphur was dissolved.

The next year Helm attacked the problem from the side of the organic sulphur constituents.* He tried the action of alcohol, ether, benzene, and alcoholic potassium hydroxide on coal with the idea of extracting all the organic sulphur. Nothing definite, however, resulted from this work.

Ferdinand Fisher followed up the work of Drown on the separation of the inorganic from the organic sulphur.† He treated samples of powdered coal with water and then added bromine gradually. At the end of five hours the reaction was complete, but when the water had been heated to 70 degrees Centigrade before beginning the experiment, the time required was only one-half hour. The mixture was filtered, and sulphur and iron were determined in the filtrate.

Bromine reacts with pyrites as follows:



The pyrites should therefore all pass into solution, and both the iron and sulphur would be found in the filtrate. Fisher at this time recognized that iron existed in other forms besides pyrites, since the residue from these extractions contained considerable iron. The ratios between the percentages of iron and sulphur in the filtrate were variable and did not indicate that only the pyrites was extracted. In some cases the sulphur was higher than indicated by the formula FeS_2 , while in others the sulphur was lower. This latter discrepancy was explained by assuming that another form of iron went into solution or that all the sulphur had not been made soluble. Apparently no dilute hydrochloric-acid-soluble-iron nor sulphur had been determined on the coals used as samples.

Fisher believed that his method was not safe as a means for determining the inorganic as distinguished from the organic sulphur, since some of the organic sulphur might be oxidized by the bromine to sulphate and since some of the sulphate might be taken up by unsaturated

*Archiv für Pharmacie, 38, 1882.

†Zeitschrift für angewandte Chemie, p. 764, 1899.

organic compounds. From his investigations, he came to the conclusion that the larger part of sulphur in coal was in the organic form, a fact which had not received much consideration before that time.

In more recent years a method has been used for the determination of the different forms of sulphur in coal depending on certain assumptions regarding the structure of coal. In the first place, all the iron not soluble in dilute hydrochloric acid is assumed to be combined as pyrites, and the pyrite sulphur is therefore estimated on the basis of FeS_2 . Iron, however, may exist as the silicate, sometimes in large quantities; so there is a very weak point in this scheme of analysis. The sulphur soluble in dilute hydrochloric acid is taken as the sulphate sulphur, undoubtedly a correct assumption. After these two forms of sulphur are determined, the others are regarded as organic sulphur. No proof has as yet been given, however, that the remainder is entirely organic sulphur. Because of the assumptions on which this method depends and the indirect manner of obtaining results, some effort has been made to get a more direct and more nearly exact procedure.

In 1915, E. F. Charlton performed some experiments in the Chemistry Laboratory of the University of Illinois to obtain a direct method for the determination of organic sulphur in coal. His process was essentially the phenol extraction method of Parr and Hadley, previously described. The residue and extract were therefore analyzed by sodium peroxide fusion for their sulphur content. His procedure was based on the theory that the residue or insoluble portion of the coal left after the phenol treatment contained all the inorganic sulphur and that the portion soluble in phenol contained all the organic sulphur. This hypothesis seemed to apply in the case of low-sulphur coals, but in high sulphur coals the amount of sulphur remaining in the insoluble residue was so excessive as compared with iron present that it was impossible to assign such sulphur to any mineral combination. Hence the question arose whether the phenol was taking out all the organic sulphur and leaving an unknown inorganic form still remaining in the residue, or whether the phenol was indeed not extracting all the organic sulphur. That the extracted sulphur compounds were organic was definitely proved by the fact that the soluble material left no ash on ignition.

APPENDIX III

CHANGES IN THE FORMS OF SULPHUR IN COAL

When coal is allowed to remain exposed to the air for any length of time, certain fundamental changes take place, the exact nature of which has been only partially determined. Since these changes affect the heating and coking value of the coal to a great extent, numerous investigations have been made in order to learn the conditions which will prevent the occurrence of these changes.

Parr and Hamilton* have reviewed some of the work done on this problem and from their own observations have come to the following conclusions:

- (1) Submerged coal loses no heat value.
- (2) Outdoor exposure causes loss of heat value from 2 to 10 per cent.
- (3) High sulphur coals oxidize in the open more than under cover, since the oxidation of the sulphur promotes other disintegration.
- (4) The main loss occurs in the first five months after mining.

Even when coal samples were sealed tightly to eliminate all air, considerable deterioration occurred. Parr and Wheeler† have shown that the heating value of coal kept under these conditions may decrease as much as 4.3 per cent. Gases seem to be given off continually, but with the greatest volume during the first two or three weeks of storage. Oxidation also occurs, due probably to the absorption of some oxygen.

In 1910 M'Callum conducted an investigation to determine the effect of different percentages of organic and inorganic sulphur in the coal on the amount of residual sulphur when the coal was coked.‡ The coal used was from Nova Scotia. It was finely ground and then separated into different samples by using solutions of different specific gravities. By this method, five samples were obtained and analyzed for their organic and inorganic sulphur content. This analysis was made by calculating the sulphur which would unite with the total iron to form pyrites and by calling this the inorganic sulphur. The remaining sulphur was considered as organic. M'Callum claimed that no sulphate

*Economic Geology, Vol. 2, p. 693, 1906.

†"The Deterioration of Coal Samples." Univ. of Ill. Eng. Exp. Sta., Bul. 17, 1907.

‡Chemical Engineer, Vol. 11, p. 27, 1910.

sulphur was present. He believed also that silicate iron was so low that it might be disregarded. He apparently did not determine the dilute-hydrochloric-acid-soluble iron. With these very evident sources of error in his scheme of analysis, however, he found that the five samples varied in organic sulphur content from 37 per cent of the total sulphur to 85 per cent.

Each of these samples was then coked to get the relative amounts of volatile and residual sulphur. Where the organic sulphur was present as 37 per cent of the total sulphur, the volatile sulphur ran 33 per cent, and where the organic sulphur was 85 per cent, the volatile sulphur ran 52 per cent. No definite relationship seemed to exist between the amount of organic sulphur and the volatile sulphur, except that, in general, where the organic sulphur was high, the volatile sulphur was also high. This experiment seemed to disprove one of the old theories that coking a coal drove out all the organic sulphur and one-half of the pyritic sulphur. His conclusion was that "a very considerable part of the organic sulphur is volatilized."

Bradbury* as early as 1878 studied the forms of sulphur in coke. He treated the finely powdered coke with dilute hydrochloric acid and collected and determined all the hydrogen sulphide given off. The dilute hydrochloric acid solution was analyzed for sulphate sulphur and for iron. The residue was then treated with concentrated aqua regia and potassium chlorate and this solution was also analyzed for sulphur.

His results showed that only a small portion of the total sulphur of the coke existed as sulphide sulphur, that practically none existed as sulphate sulphur, and that even the strong oxidizing influence of the aqua regia-potassium chlorate mixture failed to take out more than a small part of the total sulphur. From these results he concluded that the larger part of coke sulphur was in an organic form. Practically all the iron of the coke was dissolved by the dilute hydrochloric acid; thus the iron pyrites of the original coal had been completely decomposed during the coking process.

*Chemical News, Vol. 38, p. 147, 1878.

LIST OF PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION

- Bulletin No. 1.* Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904. *None available.*
- Circular No. 1.* High-Speed Tool Steels, by L. P. Breckenridge. 1905. *None available.*
- Bulletin No. 2.* Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905. *None available.*
- Circular No. 2.* Drainage of Earth Roads, by Ira O. Baker. 1906. *None available.*
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- Bulletin No. 16.* A Study of Roof Trusses, by N. Clifford Ricker. 1908. *None available.*
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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN No. 112

MAY, 1919

REPORT OF PROGRESS
IN
WARM-AIR FURNACE RESEARCH

CONDUCTED BY
THE ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS

IN COÖPERATION WITH

ERRATA

- Page 33, line eight: *for "one" read "two"*.
Page 42, Table 5, fifth column, third line from top: *for "Q-4" read "A-4"*.
Page 43, line two of text: *for "2.56" read "4.3"*.
Page 43, line three of text: *for "65.38" read "67.32" and for "34" read "32"*.
Page 57, line seventeen: *for "1919" read "1918" and for "January 16, 1918" read "January 16, 1919"*.

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THE ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS
IN COÖPERATION WITH
THE
NATIONAL WARM-AIR HEATING AND VENTILATING
ASSOCIATION

BY
A. C. WILLARD
PROFESSOR OF HEATING AND VENTILATION

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REPORT OF PROGRESS IN WARM-AIR FURNACE RESEARCH

I. PRELIMINARY STATEMENT

This Bulletin is a preliminary report of progress under the present coöperative agreement between the National Warm-Air Heating and Ventilating Association and the University of Illinois for an investigation of warm-air furnaces and furnace heating systems. The agreement was formally approved in August and became operative on October 1, 1918. Such work as is here reported was done between October, 1918, and May, 1919, and the results are set forth in a more or less summarized form giving such information and typical test data as will prove of most interest to the Association for consideration at its meeting in Columbus, Ohio, on June 11, 1919.

Under the terms of this present agreement, the Association is to provide funds in an amount not to exceed \$8,000 for a period of one year to defray part of the expense of this research work. The University through its Engineering Experiment Station is to assume the responsibility of maintaining the necessary staff and conducting the investigation and, of course, it is further responsible for the reliability and unbiased character of all results obtained. To this latter end, the Engineering Experiment Station reserves the exclusive right to publish any and all test data and results. Such publication will be made from time to time in official bulletins of the Station for the purpose of furnishing whatever scientific and technical data are developed in this work for the benefit of the engineering profession and the warm-air furnace industry.

It should be noted at the outset of this discussion that the fundamental ideas involved in the methods used in this investigation, as well as the furnace plant itself and its essential features, were developed and put into operation by the Department of Mechanical Engineering of the University of Illinois in the spring of 1918. Realizing the great possibilities in extending the scope and value of the investigation by enlisting the active support and interest of the Manufacturers' Association, a formal proposal for a coöperative investigation, presented in Appendix II, was made to the Association in June, 1918, at its annual meeting in Milwaukee, Wisconsin. This proposal received the unqualified approval of the Association.

Objects of the Investigation

The principal objects of the investigation are briefly stated as follows:

- (1) To determine the efficiency and capacity of commercial warm-air furnaces under conditions similar to those existing in actual installations with leaders, stacks and registers to form a complete system.
- (2) To determine satisfactory and simple methods for rating furnaces so that the proper size and type of furnace can be definitely selected for the service required.
- (3) To determine methods of increasing the efficiency and capacity of furnace heating equipment and the advantages or desirability of certain types of design.
- (4) To determine the heat losses in furnace heating systems and the value of insulating materials as affecting the economy of the furnace or the leaders and stacks, and finally of the system as a whole.
- (5) To determine the proper sizes and proportions of leaders, stacks, and registers supplying air to first, second and third floors.
- (6) To determine the friction losses in the cold air or recirculating ducts and registers and their proper size, proportions and arrangement or location.
- (7) Eventually, to make a study and comparison of outside and inside air circulation as affecting the economy and operation of furnace systems.



FIG. 1. THE MAIN PLANT, SHOWING PRESENT ARRANGEMENT.
NOTE INLET CALIBRATION PLANT AT THE LEFT

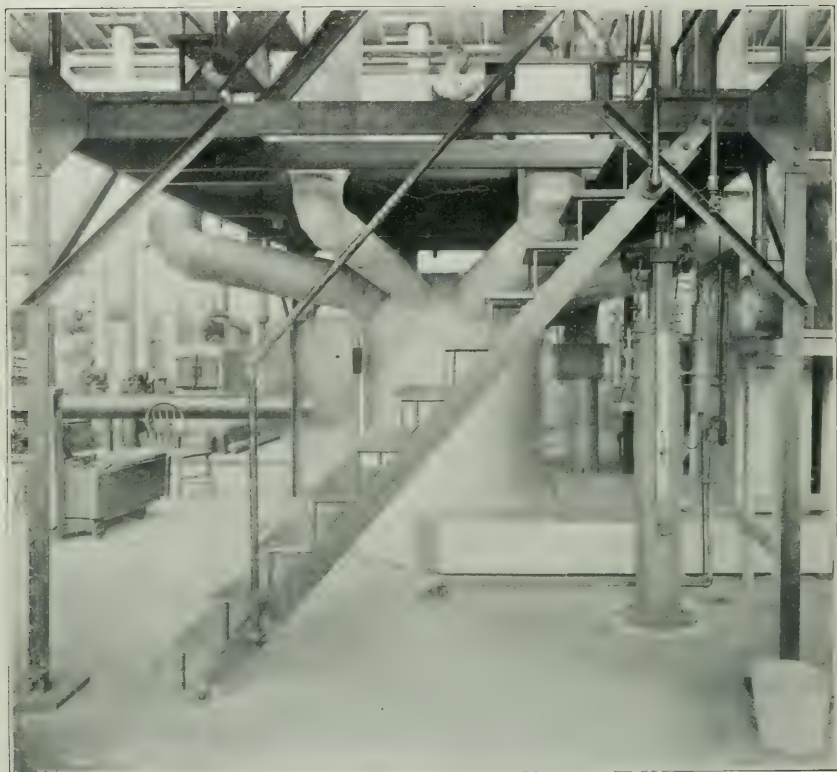


FIG. 2. SIDE VIEW OF MAIN PLANT, SHOWING UEHLING CO₂ APPARATUS AT RIGHT, WITH AIR INLET CONNECTIONS BEHIND UEHLING APPARATUS

II. SPECIAL PROBLEMS INVOLVED IN THE MEASUREMENT OF TEMPERATURES

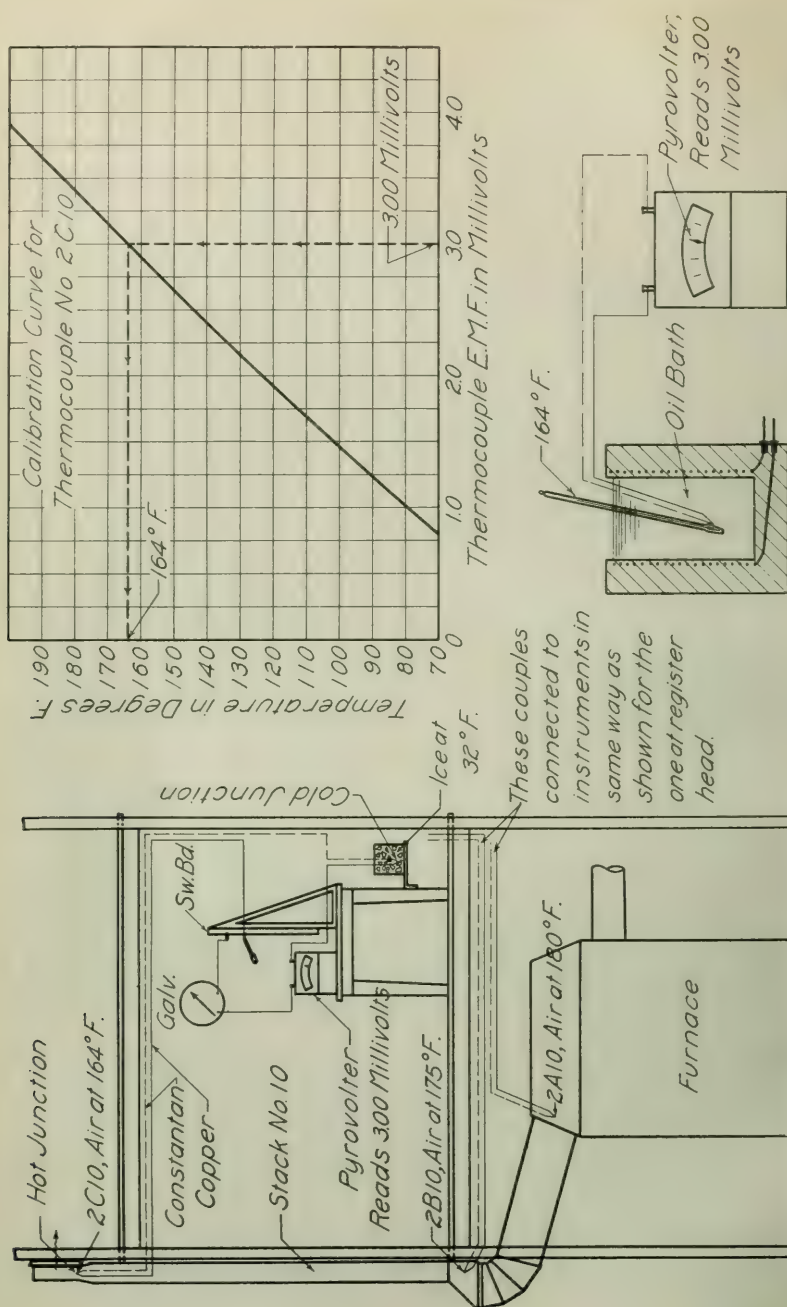
This investigation involves two special problems the correct solution of which is absolutely vital to its success. Their existence was recognized from the outset, and the difficulties involved in their solution account for the fact that practically no testing work using a complete plant has ever been done in the field of gravity furnace heating.

Measurement of Temperatures

The first problem involves the accurate measurement of air temperatures at a great many points ranging from the air inlet, through the furnace casing to the bonnet, and then through leaders, boots and stacks to the register outlets on the various floors. From a consideration of the fact that a ten-leader plant (Figs. 1 and 2) is in operation in these tests it will be apparent that from forty to fifty or more temperatures must be measured, checked and recorded every time a set of readings is taken during a test. As from five to six sets of readings are necessary on each test it is evident that a very elaborate and an accurate system (Fig. 3) of temperature measurement is required.

By the use of thermocouples which are connected to a very sensitive milli-voltmeter and galvanometer located at a central switch-board (Fig. 4) these various temperatures are quickly and accurately indicated in terms of electrical units which are later converted into degrees Fahrenheit for use in making computations. This important and unusual feature of the testing plant has been developed by Professor A. P. Kratz who has also devised a very convenient portable equipment in the shape of an electrically heated calibrating apparatus for checking the accuracy of any thermocouple at any time without removing it from the plant.

Discussion of the Temperature Measurement System Now in Use. — Since the temperatures to be measured in this investigation are in most cases comparatively low, and hence the electromotive force in the circuit small, the use of the deflection method was considered inadvisable because the readings in this case are not independent of the resistance in the circuit and are liable to errors due to change in this resistance. The Pyrovolter was found to be sufficiently accurate for the purpose



Calibration of Thermocouple

FIG. 3. DIAGRAM OF TEMPERATURE MEASURING SYSTEM, SHOWING METHOD OF USING AND CALIBRATING THERMOCOUPLES

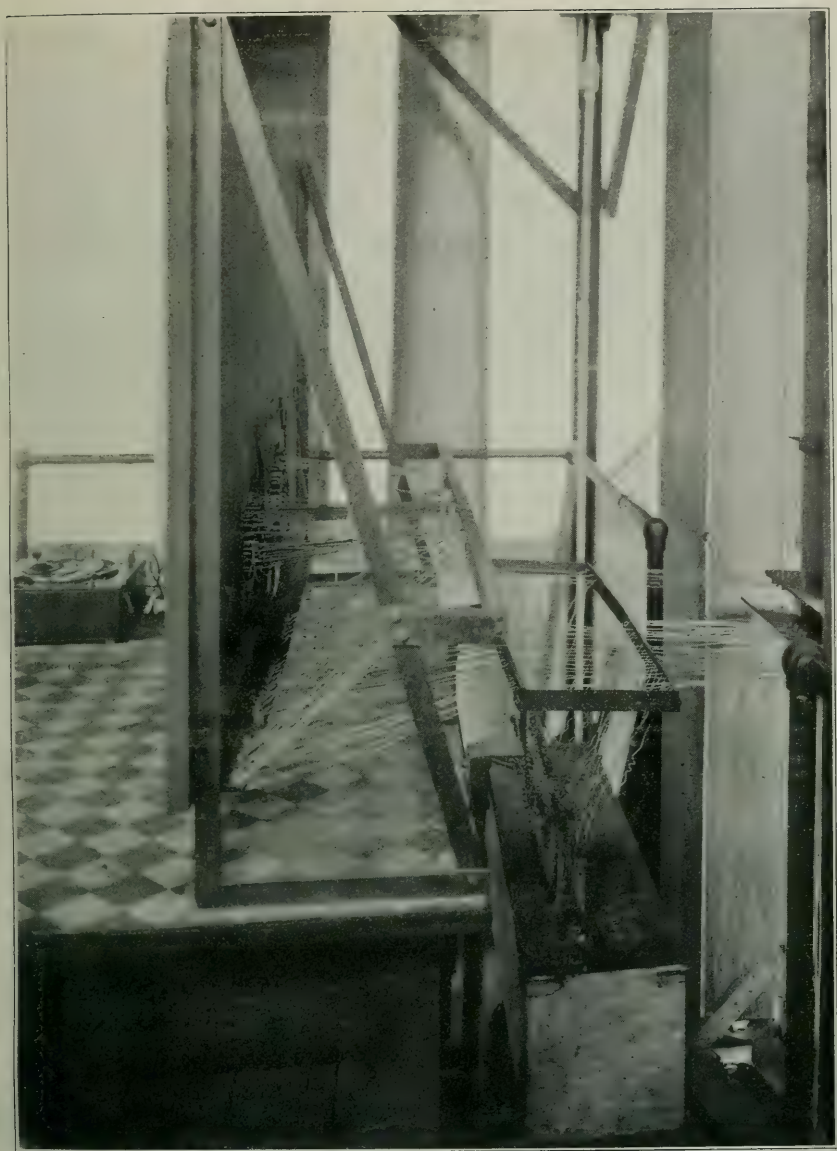


FIG. 4. THERMOCOUPLE SWITCHBOARD SHOWING PYROVOLTER, COLD JUNCTION BOX, AND WIRING CONNECTIONS

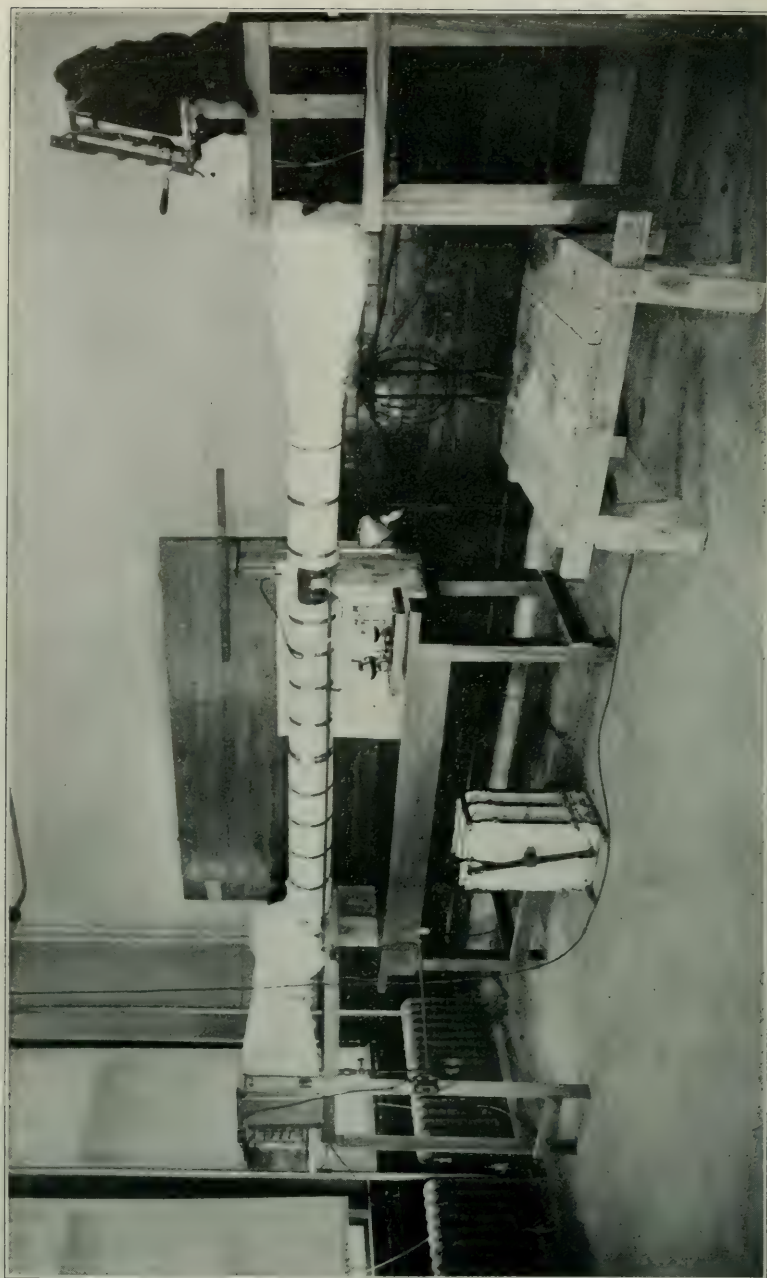


FIG. 5. ANEMOMETER CALIBRATING PLANT FOR OBTAINING CORRECT OUTFLOW AT REGISTER FACES

in view, and since the principle involved embodies the measurement of the electromotive force with zero current in the circuit, the same as with the potentiometer, thus making the readings independent of the external resistance, it was adopted. In using this instrument, the electromotive force of the couple is balanced against the fall of potential across a fixed resistance, and the current which produced this fall is immediately read on a galvanometer placed in the circuit in which the fixed resistance is located. The galvanometer is calibrated to read fall of potential instead of current, thus giving the electromotive force of the couple directly. The permanency of calibration is, therefore, a function of the permanency of the magnet in the galvanometer, while the precision of reading is a function of the accuracy with which the initial balance was attained. The accuracy of the initial balance was greatly increased in the present case by the addition of a sensitive auxiliary galvanometer placed in the thermocouple circuit.

Two factors influenced the choice of metals from which the couples were made. The first of these, i. e., the homogeneity of the metal, affects the permanency of calibration. Non-homogeneous metals are liable to change after a period of service, producing a more or less permanent change in reading, and are also liable to the production of parasitic currents causing temporary inconsistencies in readings. The second of these factors, i. e., the magnitude of the induced electromotive force per degree difference in temperature between the hot and cold junction, affects the precision of reading. The metals chosen as having the most fortunate combination of the two characteristics mentioned were copper and a copper-nickel alloy known under the trade name of constantan. This combination gives a precision of about 42 deg. F. per millivolt. The pyrovoltmeter in use was especially constructed to give a direct reading of 0.01 millivolt. Accordingly, the precision attainable is 0.42 deg. F. It has been found possible to repeat readings to within 0.01 millivolt, or 0.42 deg. F., with the present arrangement when the hot junction was placed in a constant temperature bath at 68 deg. F. This was done with a series of six readings covering a period of one-half hour. It has also been found that calibrations can be repeated to within less than two degrees, with couples subjected to the present service. A recalibration of similar couples after several months continuous service in a boiler flue at about 600 deg. F. also proved that the reading had not changed more than about two degrees. It is, therefore, considered that the readings of the couples are reliable, and are accurate within one or two degrees.

The junctions of the couples were all formed by fusing the two wires together in an air-gas flame. It was found possible to form a strong joint in this manner. Some question was raised concerning this joint on the basis that it was an oxide joint and not a metal to metal joint. An examination of the joint did not seem to bear out this contention. A series of experiments proved that no difference could be detected between couples having this type of junction and the same couples using a silver soldered joint. The fused junctions have, therefore, not been changed. The fact that the wires may be of small size, No. 22 B. & S. Gage in this case, tends to minimize the effect of radiation to or from the couple, and further the fact that the reading is independent, to a large extent, of the depth of immersion, reduces the liability of error in the determination of the actual temperature of the medium.

Correction for Radiation Effect.—It is very difficult to get the true temperature of air flowing over a highly heated surface and a special study must be made of the thermocouples used in the furnace bonnet in order to correct for the radiation effect to which they are subjected. This correction has, however, already been approximately determined by the furnace research staff in the following manner.

A typical leader (Leader No. 2 in Fig. 16) was lagged between the bonnet and the boot with two inches of hair felt, and a series of readings of the temperatures taken at the two points. The hair felt was then removed and a second series of temperature readings taken. In case the reading of the thermocouple in the bonnet had not been affected by radiation, the reading of this couple and the one in the boot with covered leader should have been very nearly the same, since there was practically no heat loss between the two points. The difference shown in the test was 28 deg. F. This difference was attributed to the radiation effect of the hot surfaces on the couple at the bonnet. As the air probably lost some heat between bonnet and boot, although the leader was covered, this difference should have been reduced one or possibly two degrees in estimating the radiation effect. It is certainly as great as $28 - 2 = 26$ degrees and probably amounted to 27 deg. F. in the preceding case. The uncovered leader showed a loss of 33 deg. F. by the subtraction of the readings of the couples at the bonnet and boot. Deducting the 26 deg. F., attributed to radiation effect on the couple at the bonnet from this difference in temperature, gives 7 deg. F. as the approximate loss between bonnet and boot in the 4 feet of un-

covered 12-inch leader pipe with an air velocity of 131 feet per minute in the leader.

TABLE 1
TEST FOR RADIATION EFFECT ON BONNET THERMOCOUPLES
(2-11-19)

	LEADER No. 2 UNCOVERED	LEADER No. 2 COVERED
Bonnet Couple.....	194° F.	195.5° F.
Boot Couple.....	161	167.3
Difference in temperature.....	33	28.2 -

NOTE.—True loss in uncovered leader, allowing 2-degree drop when covered, gives
33—26.2 = 6.8 deg. F.

TEST FOR VELOCITIES IN LEADER NO. 2 UNCOVERED
(2-10-19)

Anemometer reading at register face = 169.5 ft. per min.

True velocity at face = 225.0 ft. per min.

True velocity in leader = $225 \times \frac{458}{785}$ = 131 ft. per min.

Temperature air leaving register = 165° F.

It is also planned to make a study of this radiation effect using the method suggested in Bureau of Mines Bulletin 145, "Measuring the Temperature of Gases in Boiler Settings," Kreisinger and Barkley, and by use of the auxiliary single leader testing plant.

III. SPECIAL PROBLEMS INVOLVED IN THE MEASUREMENT OF AIR VELOCITIES

The second problem is far more difficult of solution than the preceding one and involves the measurement of air flow at the very low velocities or heads occurring in gravity warm-air furnace systems.

It will be evident that no furnace can be tested for efficiency, capacity or rating unless it is possible to determine accurately the amount of air entering the cold air or recirculating inlet and also to measure with equal accuracy the distribution of this air to each of the floors above the furnace.

In order to accomplish the latter object, it is necessary to measure the outflow of heated air at each register face while the test is in progress, and not interfere in any way with the natural operation of the system. The velocities at all these points are small, only a few feet per second at the most, and air measuring instruments which would be quite suitable at higher velocities are either useless, or else subject to serious errors when used at these low rates of flow.

After a great deal of preliminary work in the winter of 1917-1918 it was finally decided to attempt what might be called a "combination scheme" of measurement. In this scheme an instrument which is quite suitable for use at high velocities is used to "check," and give the proper correction factor for the reading which is actually taken by a low velocity instrument best adapted to the conditions to be met in the furnace testing plant.

This "checking" or calibrating work has all been done in two specially designed plants. These plants are constantly available for recalibrating the low velocity instruments at any time, *under the identical conditions as regards air temperature, rate of flow, shape of inlet or outlet, and kind and size of register that exist in the main or auxiliary testing plant.*

Calibrating Plant for Anemometers Used at Register Faces.—The calibrating plant for the hot side of the system (Figs. 5 and 6) consists of an electric heater for warming the air to any desired temperature as it is drawn in by a small centrifugal fan. This fan discharges the air through a cylindrical pipe five inches in diameter where the velocity is relatively high so that a Pitot tube may be used as the standard*

*It should be noted that this Pitot tube and air pipe have themselves been checked by the Engineering Experiment Station Staff by still more elaborate and painstaking methods which will be discussed in another bulletin.

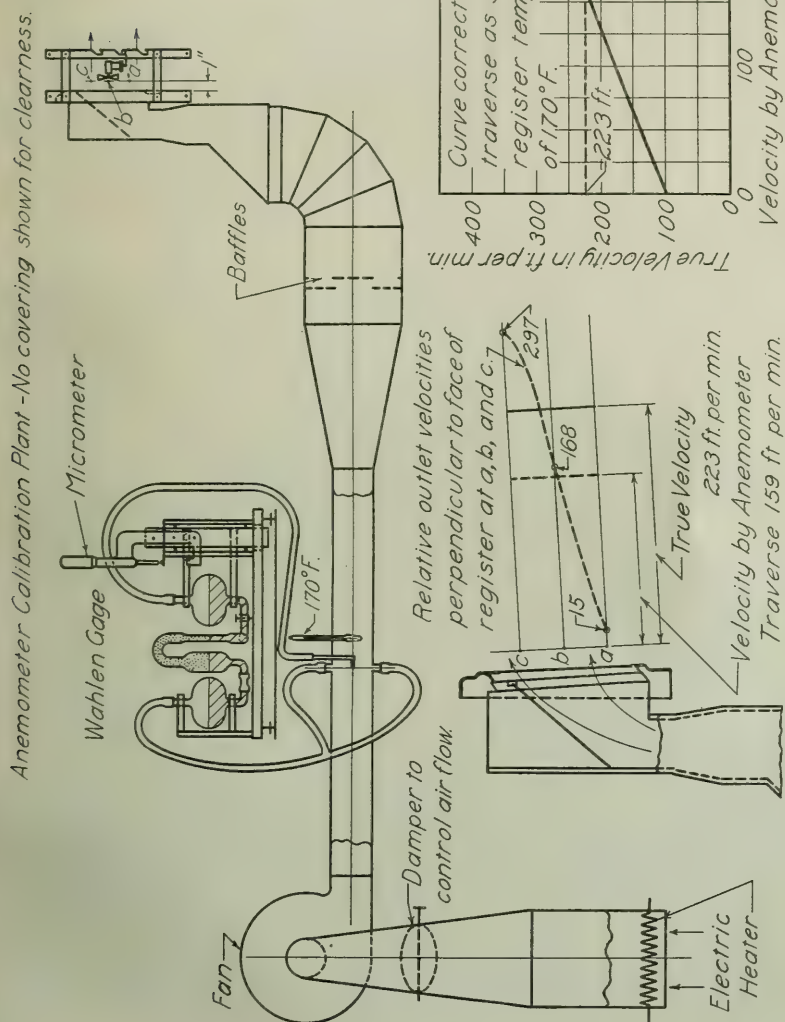


FIG. 6. SECTIONAL VIEW OF PLANT FOR CALIBRATING REGISTER OUTLET ANEMOMETERS, SHOWING DETAILS OF OPERATION

measuring instrument. After the air passes the Pitot tube, it enters an enlarged and well baffled section connecting directly to a standard elbow which turns up into a register box fitted with a sidewall register, as shown in Fig. 5. This register, box and boot are, of course, duplicates of the fittings used in the equipment of the large plant.

It will be apparent that if the exact amount of air passing the Pitot tube is known it is a simple matter to calculate the true volume and velocity of air leaving the register face. With the true velocity known it is now possible to calibrate the low velocity instruments, which are anemometers of the best obtainable type. Suitable cross-head guides are attached to the register frame and so arranged (Fig. 7) that the anemometer attached to the cross-head rod is forced to travel in a uniform and definite manner across the outlet air current at a fixed distance from the register face. As exactly similar guides (Fig. 8) and the same procedure are used on all registers in the main plant this same anemometer is put through exactly the same cycle of operations in running a furnace test.

In making the traverse, an initial reading of the anemometer dial is taken with the instrument in position No. 1 (Fig. 6) and a stop watch is started. The electric heater maintains the desired temperature since it is most essential that the anemometer be calibrated at the temperature existing in the test. At the end of five seconds the instrument is moved to position No. 2 and so on through twelve positions, and the final reading only is then noted. In this way it is possible to average automatically the velocity of the outflowing air which, of course, does not flow out uniformly over the area of the face. Most of the air, as is well known, issues above the center of the register face, as shown in Fig. 6. If the original reading of the dial was 3,820 and the final is 3,979 the instrument *indicates* a velocity of 159 ft. per min. at the register. The anemometer will duplicate this reading within one per cent as often as it is desired to check its performance. By calculation from the reading at the Pitot tube, the *true* velocity was found to be 223 ft. per min., and hence for this particular set of conditions the anemometer reads too low by 64 ft. per min.

It is, of course, evident that it would simplify matters greatly if a series of calibrating tests was run in advance for each anemometer. A series of curves could then be drawn (Fig. 6) from which *true* velocities at any register temperature could be found as soon as the velocity *indicated* by the anemometer on any test was known. This calibration has been done, entailing months of painstaking and exacting measure-



FIG. 7. TYPICAL ARRANGEMENT AT REGISTER FACE IN CALIBRATING PLANT
FOR MAKING ANEMOMETER TRAVERSE

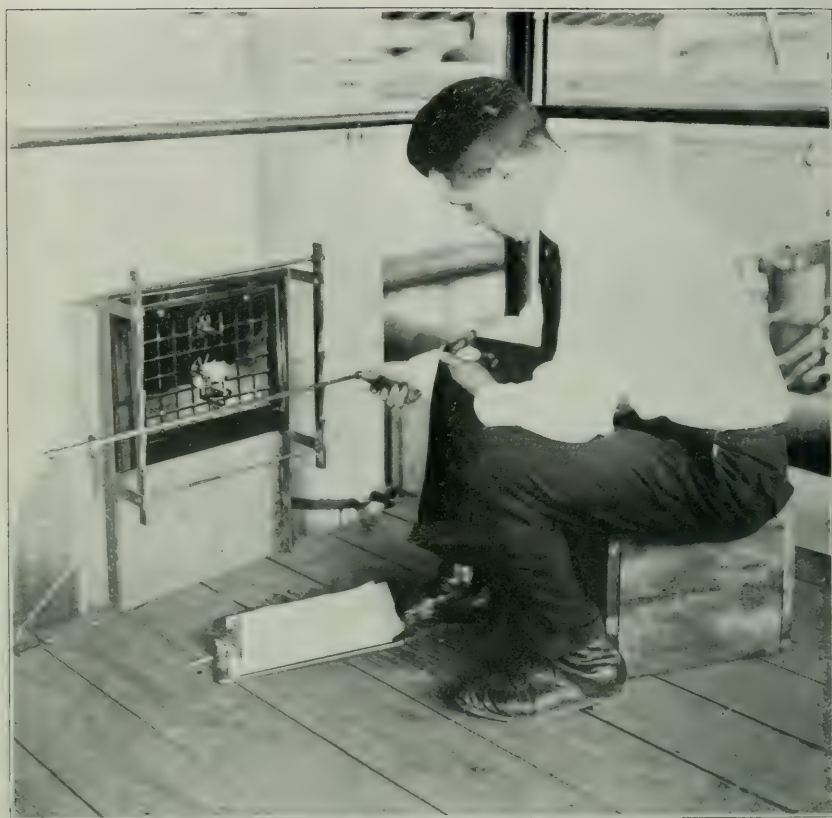


FIG. 8. METHOD OF MAKING ANEMOMETER TRAVERSE AT REGISTER FACES
ON MAIN PLANT

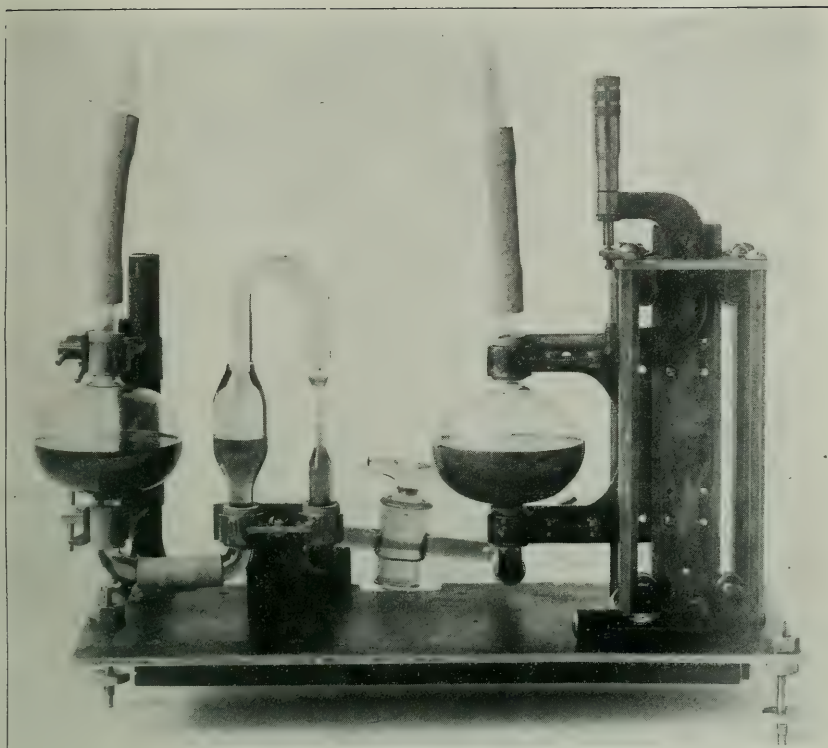


FIG. 9. THE WAHLEN GAGE, SENSITIVE AND ACCURATE TO 0.0001 INCH
ALCOHOL

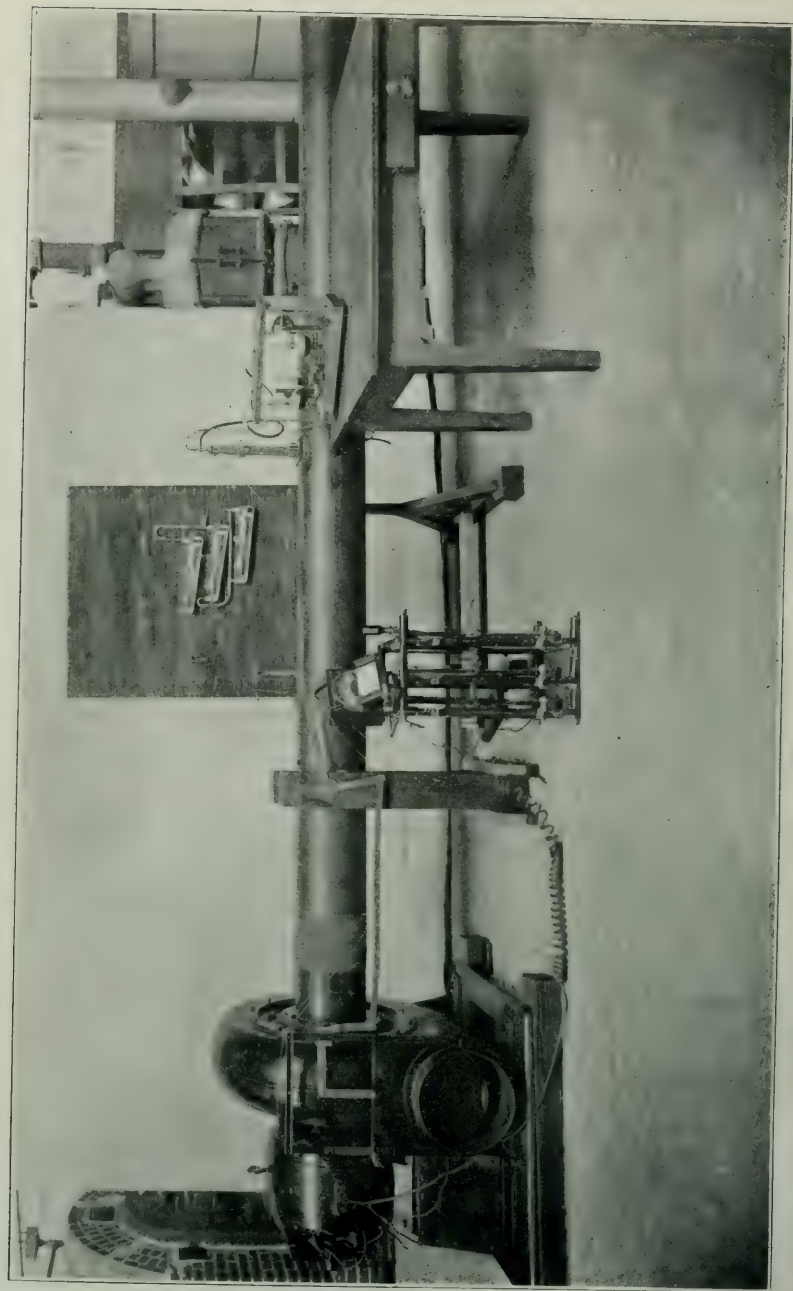


FIG. 10. THE CALIBRATING PLANT FOR THE INLET SIDE OF THE SYSTEM SHOWING THE WAHLEN GAGE IN USE

ments. The same sort of calibration data had to be secured for the cool air inlet anemometers, as well as for those used on the warm air outlets. It is most important to have the calibrating plant constantly available for checking the performance of any anemometer during any test.

The Wahlen Gage.—It was this calibrating work* that probably developed the greatest difficulties which have been encountered. Every possible refinement of measurement was resorted to without complete success until F. G. Wahlen (detailed to this work from the Experiment Station Staff) finally developed a remarkable gage (Fig. 9) so sensitive and accurate that it would measure a pressure head of less than $\frac{1}{10000}$ of an inch of water, and respond instantly to the slightest fluctuation in pressure. This equipment is a distinct addition to such precision instruments as are available for measuring low-pressure heads.

This gage† made it possible to duplicate readily readings with the Pitot tube used for checking the anemometer to within one per cent.

The essential features of the gage are clearly shown in the illustration, from which it will be seen that a rigid base set on leveling screws is used to support two large glass bulbs which are in communication with each other through an inverted U tube of peculiar shape. The left hand bulb is rigidly attached to the base frame, but the right hand bulb moves vertically up or down with the carriage to which it is attached. The motion of this carriage is controlled by frictionless rollers which eliminate all back lash or side sway. This movement is under the positive control of a micrometer screw, reading to 0.001 inch direct, and takes place with a slight swivelling action of the joints in the right hand connector. Pressures are communicated to the two bulbs through the flexible connectors on the top of each.

Alcohol (0.8195) about half fills the bulbs and the U tube, and a little aniline dye gives a distinctive red color. The upper part of the U tube is completely filled with a clear turpentine and ligroin mixture (0.8100) so made up that its specific gravity is 0.0095 less than the density of the colored alcohol.

In operation (Figs. 6, 10 and 19), the gage is first balanced at zero with both pressure connections open. This is easily done by bringing the meniscus in the constricted side of the U tube to a reference line engraved near the center of the tube and then reading the micrometer.

*Prof. S. L. Simmering devoted practically all his time to this problem until April 1, 1919, when he resigned to accept a position at the University of Colorado.

†See a more detailed description of this instrument in a separate paper entitled the "Illinois Micromanometer" by F. G. Wahlen.

This zero setting can be accomplished (without using a microscope) to within 0.0001 of an inch of alcohol, equivalent to about 0.00008 of an inch of water. Pressure connections are then made and the movable carriage and its liquid bulb so manipulated that the meniscus is brought back to the reference line on the U tube and the micrometer read again. In fact, by proper use of the stop cock in the connecting arm of the gage this meniscus is never allowed to move out of the constricted tube at all. The difference between the two micrometer readings when multiplied by the density of the alcohol gives the pressure head in inches of water. A final zero reading is always taken and must check to 0.0002 of an inch with the original zero. As the density of the alcohol varies with its temperature a density-temperature calibration curve is used, and the gage is enclosed in a glass case as shown in Figs. 10 and 19 where it is seen in use.

It will be evident from the preceding statement that as there has been no movement of the measuring liquid no corrections are necessary for capillarity, viscosity, variations in bore of tubes, or conditions of glass surface. The sensitiveness of the gage depends (1) upon the relation between the areas of the constricted tube and the large cross section of the bulbs, (2) upon the viscosity characteristics of the two liquids and the small density differential, and (3) upon the fact that the constricted part of the U tube is very short. All other connections are large and free. A standard machinist's precision micrometer forms the measuring element of the gage which is accurate within the range of measurement.

Calibrating Plant for Anemometers Used at Inlet.—The calibrating plant (Fig. 10) for the cold side of the system consists of a cool air inlet opening of exactly the same size and arrangement (Fig. 11) as that used on the furnace plant itself (Fig. 12). This opening is equipped with crosshead guides and traverse rod for carrying the anemometer across the face. This large duct then tapers (Fig. 1, see lower left-hand corner) to connect with a steel pipe 10 inches in diameter in which a Pitot tube is placed for checking the actual weight of air flowing. A large fan at the outlet end is arranged with variable speed control to handle such volumes of air as correspond to the amounts entering the furnace plant under the various test conditions. In this inlet calibrating plant the *indicated* and *true* velocities of the inlet air are obtained in a manner similar to that already described, and suitable calibration curves have been drawn. The Wahlen gage has proved as essential here for accuracy and refinement of readings with the Pitot tube as in

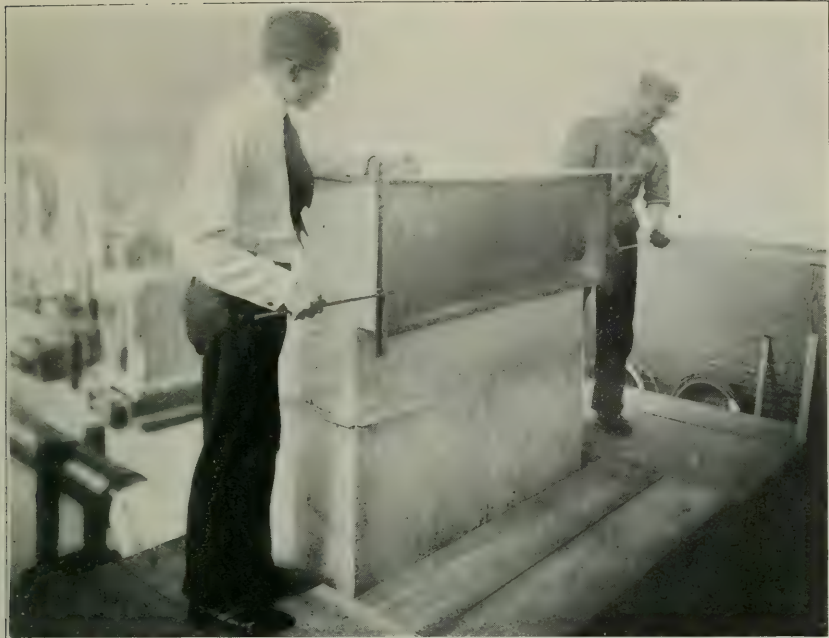


FIG. 11. METHOD OF MAKING TRAVERSE AT THE INLET OPENING OF THE CALIBRATING PLANT FOR MEASURING RECIRCULATED AIR

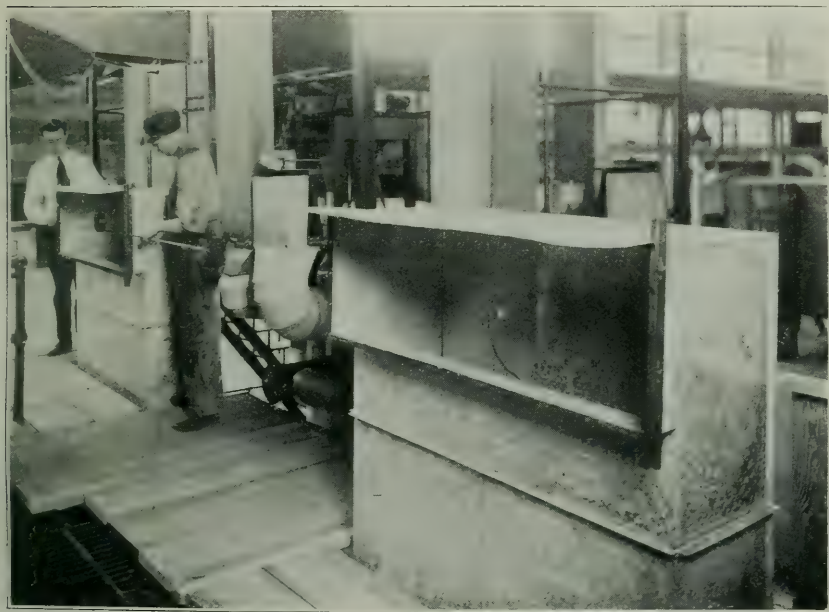
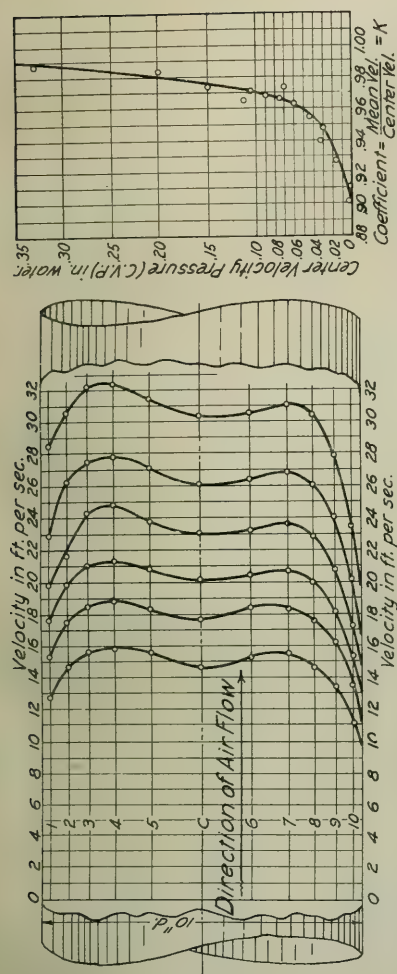


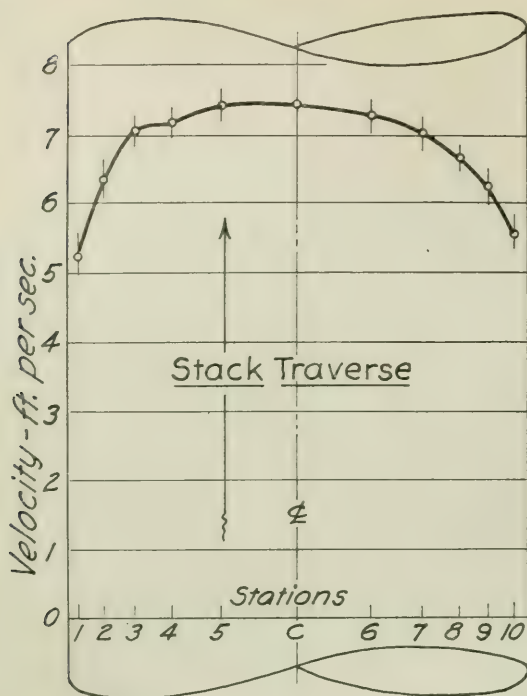
FIG. 12. MEASURING THE AIR ENTERING THE FURNACE AT THE INLET OPENING WHICH IS AN EXACT DUPLICATE OF THE OPENING ON THE CALIBRATING PLANT IN THE RIGHT FOREGROUND



Position	Pitot	C.V.P.	Velocity	C.V.P.	Velocity	C.V.P.	Velocity	C.V.P.	Velocity	C.V.P.	Velocity	C.V.P.	Velocity	C.V.P.	Velocity
1		.0319	12.68	.0514	15.30	.0681	17.60	.0871	19.90	.1158	22.92	.1577	28.5		
2		.0426	14.67	.0675	17.53	.0875	19.94	.1156	21.60	.1521	26.30	.2057	30.7		
3		.0483	15.60	.0755	18.54	.0970	21.00	.1295	24.30	.1673	27.55	.2268	32.2		
4		.0500	15.88	.0785	18.90	.0998	21.30	.1350	24.80	.1700	27.80	.2296	32.4		
5		.0484	15.60	.0744	18.41	.0961	20.90	.1257	23.85	.1624	27.20	.2163	31.5		
C		.0451	14.51	.0691	17.72	.0891	20.17	.1170	23.10	.1507	26.22	.2016	30.4		
6		.0459	15.22	.0745	18.41	.0915	20.40	.1194	23.30	.1539	26.40	.2052	30.6		
7		.0476	15.50	.0743	18.40	.0937	20.63	.1234	23.70	.1586	26.88	.2116	31.1		
8		.0426	14.67	.0682	17.65	.0882	20.04	.1155	22.90	.1495	26.10	.2023	30.4		
9		.0352	13.32	.0572	16.12	.0728	18.20	.0957	20.80	.1272	24.08	.1700	27.9		
10		.0245	11.10	.0397	13.45	.0515	15.31	.0671	17.32	.0897	20.20	.1202	23.5		

TABLE OF CENTER VELOCITY PRESSURES, IN INCHES OF WATER, & VELOCITIES, FT./SEC.
 Note: Quantity of Air per min. = Center Velocity $\times K \times 50 \times$ Area of Pipe, sq. ft.

FIG. 13. VELOCITY CURVES FROM THE INLET CALIBRATING PLANT, SHOWING HOW CENTER COEFFICIENT VARIES WITH THE VELOCITY OF FLOW. BASED ON READINGS BY WAHLEN GAGE



Note: Round pipes are divided into five concentric rings of equal area. Stations are so taken as to give the average velocity of each air ring.

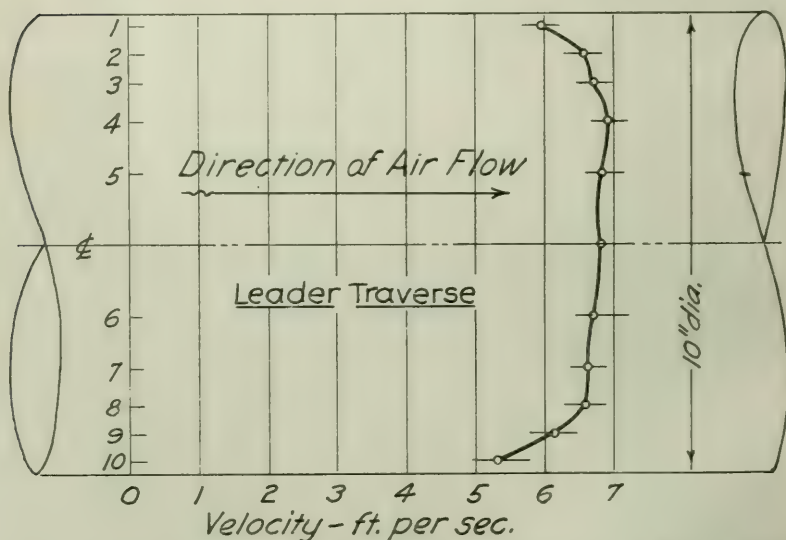


FIG. 14. VELOCITY CURVES FROM A LEADER AND ALSO FROM A STACK, SHOWING CHARACTER OF AIR FLOW THROUGH SAME

the previous calibrating work. In carrying out this calibrating work, it has been found necessary always to make a traverse of both the 5-inch and the 10-inch pipes in order to get the average velocity of air flow through the pipe at the section where the velocity pressures are measured by the Pitot tube. This variation in velocity across the diameter is large even for a fixed quantity of air passing through the pipe. The relation between the average velocity reading and the center velocity reading, $\frac{V_m}{V_c} = K$, changes, moreover, with a change in the quantity of air passing through the pipe as shown in the curves of Fig. 13 taken from the 10-inch pipe. Curves taken from a traverse of a leader (Fig. 14) on the auxiliary furnace plant show this same variation in velocity while those taken from a traverse near the head of a round stack (Fig. 14) also on the auxiliary plant show an even greater variation. The center reading is proportionately much higher, in the latter case, than the average velocity reading. The curves in Fig. 14 are merely submitted as illustrative of the sensitiveness of the Wahlen gage at low velocities and show its usefulness in studying air flow in leaders and stacks and even through the furnace casing itself. At some later period in the investigation such a study should be made, but it is the present purpose to test first the furnace and the plant as a whole.

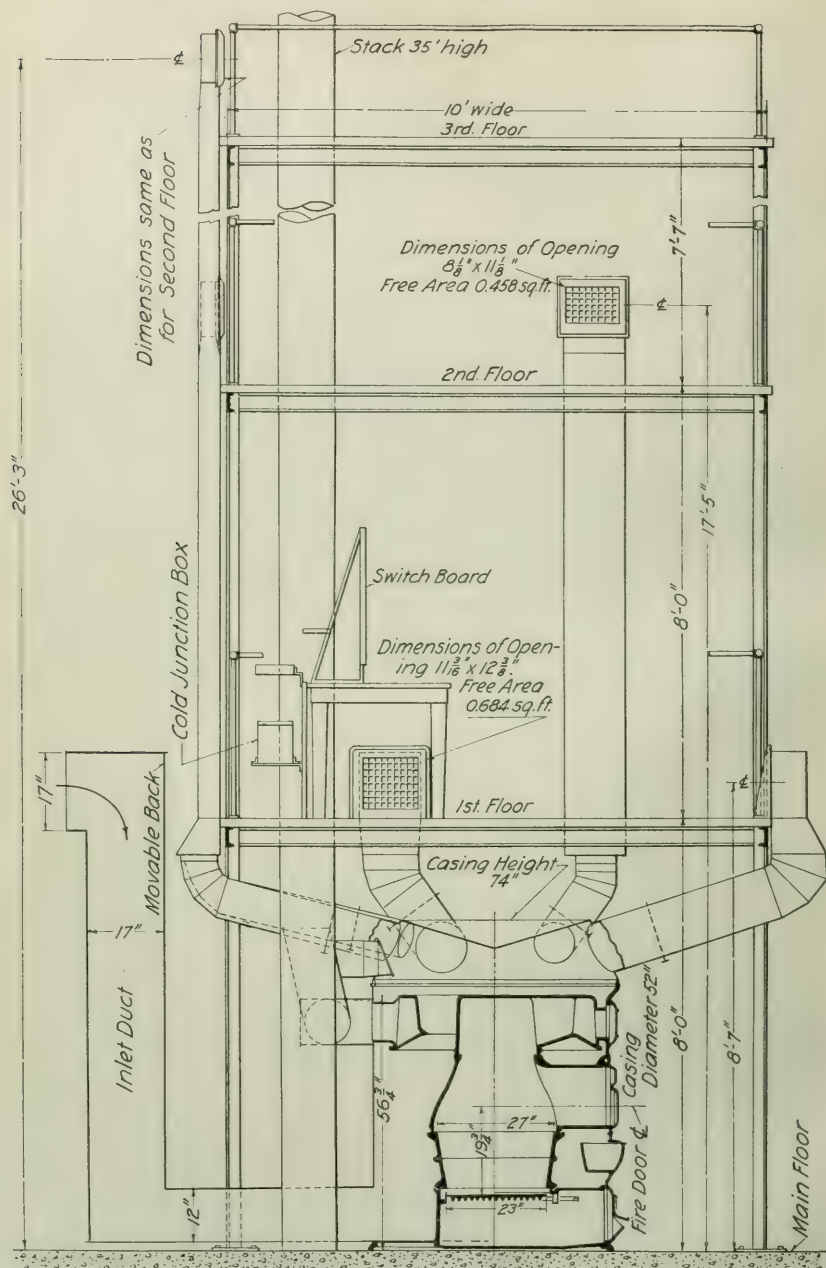


FIG. 15. SECTIONAL ELEVATION OF FURNACE TESTING PLANT

IV. THE MAIN PLANT

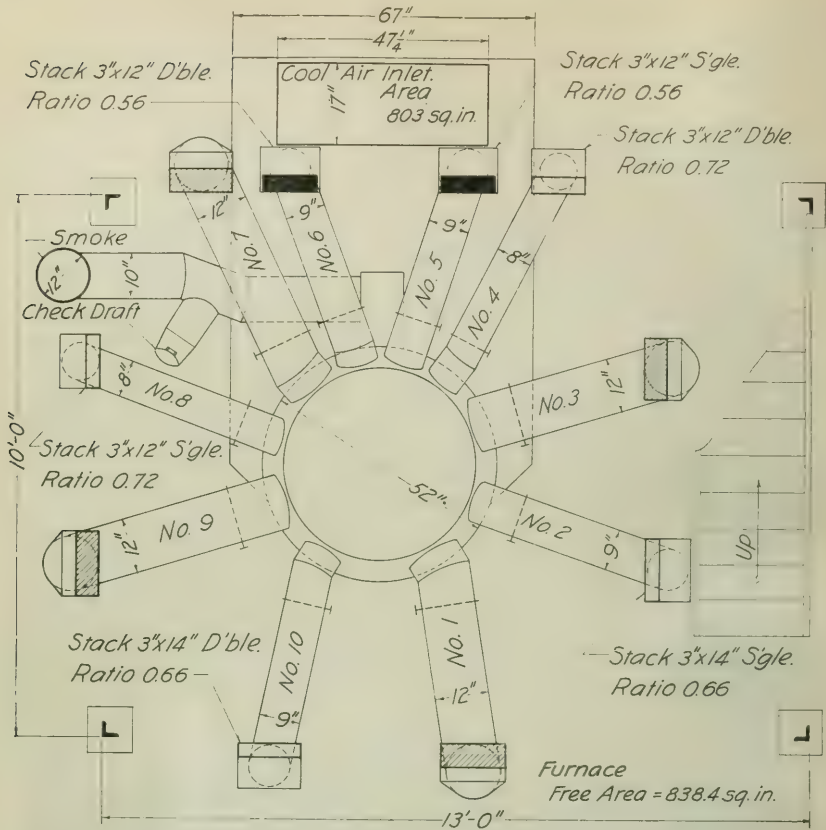
The general view (Fig. 1) of the present (April-May, 1919) main plant* shows a three-story steel structure erected in the Mechanical Engineering Laboratory. This structure merely serves as the working skeleton of a house and carries the stacks and registers which run to the various floors. All important dimensions are given in the sectional elevation and plan (Figs. 15 and 16), which show the equipment in use on May 1, 1919. A ten-leader plant is being used at present and all stacks have been cased in to simulate furred wall conditions. One of the four stacks to the second floor and one of the two stacks running to the third floor are single, but all other stacks are double wall with $\frac{5}{16}$ -inch air space. The single stacks were made 3-inch deep instead of $3\frac{1}{2}$ -inch in order to make them comparable with double wall stacks.

The side view of the furnace and leader system (Fig. 2) shows the recirculating duct and the crosshead guide at the inlet to the duct. In the right foreground is a Uehling CO₂ outfit for taking a continuous CO₂ record on all tests. A sample record is given in Fig. 17 and the performance of this instrument is checked periodically by a portable Orsat apparatus. This view also shows an observer reading temperatures at the thermocouple switchboard.

Results Obtained from Main Plant.—It has already been stated that as this is a report of progress, more or less summarized statements will be made including such typical test data as will best illustrate the scope and character of the work thus far accomplished. The first and second objects of the investigation have already been given as (1) the determination of efficiency and capacity of warm air furnaces under conditions similar to those in an actual installation, and (2) the fixing of proper methods of rating furnaces. These two objects are so dependent on each other that it is almost impossible to deal with them separately. Fairly definite conclusions must be reached concerning the *basis* for ratings before tests for efficiency and capacity can be conducted.

The following summary of test data (Table 2) from a series of seven runs on the main plant between March 14 and April 23, 1919, will

*The original main plant was found to have entirely too great a leader and stack area for the free area of the furnace and the second and third floor runs were reduced in size to the dimensions shown in Fig. 16.



	Leaders			Stacks		Registers	
	No.	Size	Area	Dimensions	Type	Dimensions	Free Area
1st Floor	1	12 in.	113 sq. in.		Asbestos Covered	11 3/8 in. x 12 3/8 in.	0.684 sq. ft.
	3	12 in.	113 sq. in.			" "	"
	7	12 in.	113 sq. in.			" "	"
	9	12 in.	113 sq. in.			" "	"
2nd Floor	2	9 in.	64 sq. in.	3 in. x 14 in.	S'gle.	8 1/2 in. x 11 1/2 in.	0.458 sq. ft.
	4	8 in.	50 sq. in.	3 in. x 12 in.	D'ble.	" "	"
	8	8 in.	50 sq. in.	3 in. x 12 in.	S'gle.	" "	"
	10	9 in.	64 sq. in.	3 in. x 14 in.	D'ble.	" "	"
3rd Floor	5	9 in.	64 sq. in.	3 in. x 12 in.	S'gle.	" "	"
	6	9 in.	64 sq. in.	3 in. x 12 in.	D'ble.	" "	"
Leader Area: 1st Fl. 452 sq. in., 2nd 228 sq. in., 3rd 128 sq. in. Total 808 sq. in.							
Percent Leader Area: 1st Fl. 55.9, 2nd 28.2, 3rd 15.8.							

FIG. 16. FLOOR PLAN AND DIMENSION TABLE FOR FURNACE TESTING PLANT

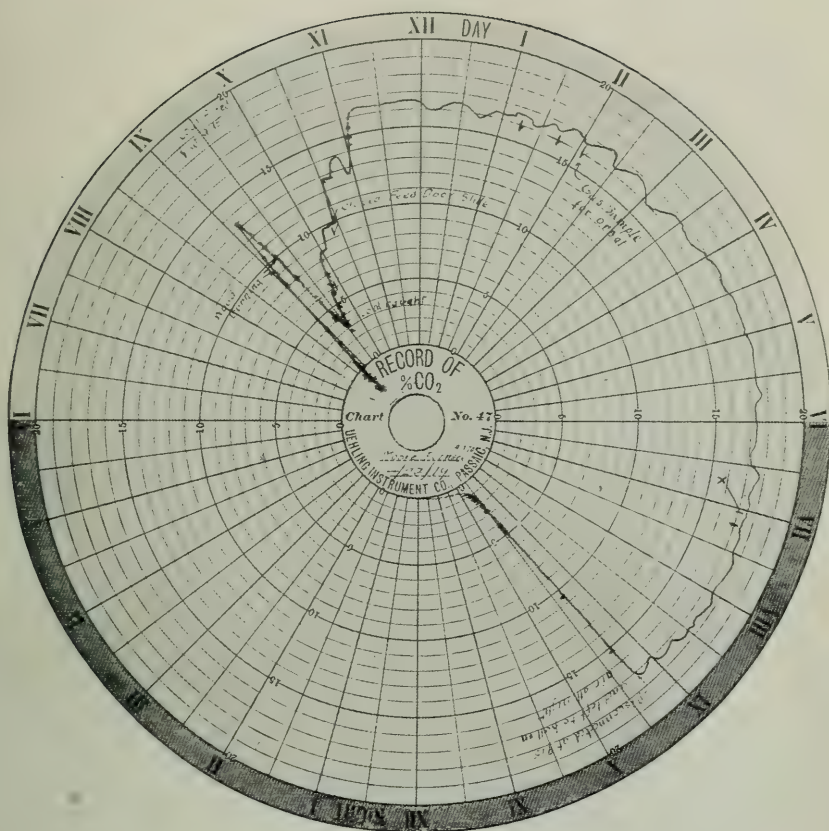


FIG. 17. SAMPLE CO_2 RECORD TAKEN BY THE UEHLING CO_2 RECORDER
FROM TEST OF APRIL 23, 1919

illustrate this interdependency previously noted and will show how the conditions of rating affect capacity and likewise efficiency.

TABLE 2

SUMMARY OF SEVEN TESTS ON THE MAIN PLANT SHOWING EFFECT OF REGISTER TEMPERATURES ON CAPACITY OF FURNACE AND LEADERS

WARM AIR FURNACE RESEARCH

ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS

Date 3-14 to 4-23-19

Name *Entire Staff*

Subject *Summary of Seven Tests Showing Effect of Register Temperature on Capacity.*

Fuel: Stove size anthracite, in solid fire pot. No draft over 0.2" of water.											
No.	TIME	Test No.	1st.	2nd.	3rd.	1st.	2nd.	3rd.	1st.	2nd.	3rd.
			Average Temperature Rise and Register Temperature. †			Average Leader Vel. in ft. per min., and per cent Weight per floor.			Average B.t.u. Available for Heating above 70° per sq. in. Leader.		
1	3-14-19	1	78.2	70.0	81.0	118.5	215	264	52	85	121
2			143.2	135.0	146.0	39.6%	35.8%	24.6%			
3		Av. Reg. Temp.	141.4								
4											
5	4-17-19	2	75.3	72.4	81.0	118.0	219	268	50	89	122
6			140.3	137.4	146.0	39.3%	36.2	24.4			
7		Av. Reg. Temp.	141.2								
8											
9	4-23-19	3	88.8	78.6	89.5	131	226	274	68	107	144
10			153.8	143.6	154.5	41.9%	36.2	21.9			
11		Av. Reg. Temp.	149.8								
12											
13	4-18-19	4	105.3	95.4	101.9	148	245	304	85	134	175
14			170.3	160.4	166.9	41.8%	34.9	23.3			
15		Av. Reg. Temp.	165.9								
16											
17	4-21-19	5	113.5	105.0	114.0	159	252	315	103	153	204
18			178.5	170.0	179.0	42.8%	34.1	23.1			
19		Av. Reg. Temp.	175.8								
20											
21	4-21-19	6	132.6	115.8	132.4	183	268	331	134	168	243
22			197.6	180.5	197.4	44.6%	33.0	22.4			
23		Av. Reg. Temp.	191.9								
24											
25	4-21-19	7	119.3	105.3	114.1	165.5	224	246	68	107	144
26			184.3	170.3	179.1	47.6%	32.4	20.0			
27		Av. Reg. Temp.	177.9								
28						Actual & Relative Leader Area					
29						452 sq. ft.	228	128			
30						56.0%	28.2%	15.8%			

Remarks: All dampers wide open except in Test No. 7. For dimensions of leaders, stacks and registers, and plant layout see Fig. 16 and Table therewith.
† Register temperatures based on air entering furnace at 65° F.

The tests will be referred to by number, and were run to determine to what extent variations in the outlet air temperatures at the registers affect the rating of a furnace when installed in a complete plant. The average outlet temperatures were 141.2, 149.8, 165.9, 175.8, 177.9, and 191.9 deg. F. based on air entering furnace at 65 deg. F. It is entirely possible to maintain register temperatures constant within a 5-degree range on any test. Tests No. 1 and No. 2 were run under the same conditions as checks on each other, and have both been submitted to show how nearly it is possible to duplicate runs on the plant at different dates. The data from No. 2 will be used in the comparisons considered in the following discussion. All tests were run with the plant as shown in Figs. 15 and 16.

Effect of Register Temperature on Leader Pipe Capacity.—The first thing discovered from a survey of these data was that a square inch of leader pipe area in a first floor leader has far less heating and air-carrying value than in a second or third floor leader as installed. In test No. 2 (Aver. reg. temp. 141.2 deg. F.), for example, a square inch of leader to first floor carries 50 B. t. u. per hour available for heating above 70 deg. F., and for a third floor leader this value rises to 122 B. t. u. per hour making *an increase* of 144 per cent. For the second floor the B. t. u. per sq. in. is 89, or *an increase* of 70 per cent.

A comparison of leader velocities for this same test shows 118 ft. per minute for the first floor, and 268 ft. per minute for the third floor, which is an increase of 127 per cent. For the second floor the increase in velocity is 85 per cent.

A still more significant discovery was made by comparing tests No. 2 (Aver. reg. temp. 141.2 deg. F.) and No. 6 (Aver. reg. temp. 191.9 deg. F.) from which it was found that a square inch of first floor leader has increased its capacity in available heating value above 70 deg. F. from 50 B. t. u. to 134 B. t. u. per hour, *a gain of 170 per cent.* For a second floor leader this value increased from 89 to 168 B. t. u. per hour or *a gain of 89 per cent.*, and for a third floor leader this value jumps from 122 B. t. u. to 243 B. t. u. or *a gain of 99 per cent.* It should be noted that these gains are very large, much larger than the increase in velocities through these leaders.

If a comparison of velocities in the leaders for these same two tests is made, it is found that the first floor leader velocities have increased from 118 to 183 ft. per min., a gain of 55 per cent. In the case of second floor leaders, the velocities have increased from 219 to 268 ft. per min.,

a gain of 22 per cent, and for the third floor leaders the velocities show an increase of from 268 to 331 ft. per min., a gain of 24 per cent.

Further comparisons of this kind at other register temperatures may be readily made by reference to the data in the table.

It should also be noted that the distribution of the air by weight to the various floors has changed with the increasing register temperatures. In Test No. 2 the relation was: First floor=39.3 per cent, second=36.2 per cent and third=24.4 per cent while in test No. 6 it changed to: First floor=44.6 per cent, second=32.4 per cent and third=21.9 per cent. In test No. 7 (Aver. reg. temp. 177.9 deg. F.) an attempt was made to increase the velocity and heating value per square inch of leader pipe supplying the first floor by dampering the second and third floor leaders. This resulted in a distribution of 47.6 per cent of the air to first floor, 32.4 per cent to second, and 20 per cent to third. By reference to test No. 5 (Aver. reg. temp. 175.8 deg. F.) which is most nearly comparable, it will be seen that the gain in velocity (Table 3) and in B. t. u. per square inch of leader pipe to first floor was small and much more than offset by the reduction in these quantities for the second and third floors.

TABLE 3
EFFECT OF DAMPERING SECOND AND THIRD FLOOR LEADERS TO INCREASE
CAPACITY OF FIRST FLOOR LEADERS

Test No.	Vel. ft. per min.			B. t. u. per sq. in.			Aver. Reg. Temp.
	1st	2nd	3rd	1st	2nd	3rd	
5	159.0	252	315	103	153	204	175.8
7	165.5	224	246	111	137	160	177.9
Gain.....	6.5			8			
Reduction.....		28	31		16	44	

It is, therefore, quite evident that the practice of dampering leaders to upper floors as a result of poor design immediately cuts down the total capacity of a plant. The slight gain in heating effect on the first floor is accomplished at a serious sacrifice both in plant capacity and efficiency. This problem is worthy of further investigation at the first opportunity.

The great significance of the data developed by these seven tests can hardly be overestimated and is the first important result of this investigation. It affects not only the basis for rating furnaces and designing furnace heating systems, but establishes very definite limits

for rating and capacity tests. It is a very simple matter to show that a furnace heating plant in a two or three story house in order to be entirely successful in the coldest weather must have a very large proportion of its leader capacity devoted to supplying the first floor if the register temperatures are to be kept as low as 150 deg. F. In fact, attempts to apply these data to an actual design worked out by W. E. Pratt with the given temperature limitation show that prohibitive leader sizes will result. A more satisfactory basis for design and also for rating requires a register temperature between 175 and 185 deg. F., which has been used by Mr. Pratt in applying these data to a typical house heating design problem to be presented at the June meeting of the Association. A summarized statement concerning the effect of these temperatures on a furnace heating design problem will be found in Section VII of this Bulletin.

It, therefore, appears desirable and necessary to recommend on the basis of the data thus far obtained that in rating furnaces in square inches of leader pipe area the leaders to first floors should be limited

TABLE 4

CHEMICAL ANALYSIS OF THE ANTHRACITE COAL USED IN THESE TESTS

ENGINEERING EXPERIMENT STATION

UNIVERSITY OF ILLINOIS

Report of Chemical Analysis by Prof. S. W. Parr and J. M. Lindgren

April 30, 1919

Chemical Laboratory No. 10675

Special Marks *Scranton Anthracite*¹ Warm-Air Furnace Trial

Proximate Analysis of Coal		Per cent for Coal as Fired
Fixed carbon		78.98
Volatile matter		6.19
Moisture		1.44
Ash		13.39
Ultimate Analysis of Coal		Per cent for Coal as Fired
Carbon (C)		79.52
Hydrogen (H)		2.43
Oxygen (O)		1.68
Nitrogen (N)		0.75
Sulphur (S)		0.81
Ash		13.39
Moisture at 105° C.		1.44

Calorific Value—B. t. u.

By Oxygen Calorimeter per pound of Air Dry Coal 127.91

¹After rejecting one shipment of hard coal it was finally decided to store 30 tons of the above coal as a uniform test fuel for running all tests.

to 100–115 B. t. u. per square inch, to second floors to 160–180 B. t. u. per square inch, and to third floors to 195–215 B. t. u. per square inch, when the average register temperature is approximately from 175 to 185 deg. F. It will also be apparent that for most of the heating season a lower register temperature, probably in the neighborhood of 150 deg. F., will be quite satisfactory, and there may be occasional days when the air at the registers must be even above 175 deg. F. for short periods as it would be poor economy to design for the coldest day that was ever recorded in a certain locality.

Efficiency and Capacity Tests.—The question of testing furnaces for efficiency and capacity may now be considered with some degree of definiteness, and it is evident that register temperatures must be made the controlling factor if the data are to prove applicable in practice. These tests should, of course, cover a reasonable range of register temperatures, as from 120 to 190 deg. F., in order to show at what register temperature a given furnace is most efficient. It should be noted here that this probably will not be the temperature at which the furnace is rated for capacity, and it is not necessary that it should be.

In addition to the preceding limitation, it was decided to observe the following conditions and procedure in this first series of tests:

(1) The fuel is to be stove size anthracite with an ash content of less than 14 per cent for dry coal.

(2) The chimney draft must not exceed 0.2 inches of water at any time during a test.

(3) The furnace is always to be started with weight of wood equivalent to 10 per cent of its coal capacity and warmed up for fifteen minutes.

(4) The test is to start at the expiration of the fifteen minute preliminary period, with one-third of the total fuel charge (based on firepot capacity).

(5) The second firing of the second one-third of the fuel charge is to be made at the end of fifteen minutes from start of test.

(6) The third firing of the final one-third of the fuel charge is to be made at the end of thirty minutes from start of test. After this firing the fire must not be touched.

(7) At the end of the test, which must not consume more than 80 per cent of the total fuel charge, the fire is to be quenched with water and drawn, and the ashpit cleaned.

(8) The residue is to be weighed and its moisture content and heat value determined.

(9) The composition of the coal used is as shown in Table 4.

The results of five complete tests, on the main plant showing variations in efficiency with register temperatures, are given herewith (Table 5), and a summary sheet of the first test of April 23, 1919, is reproduced (Table 6) as well as a graphical CO₂ record (Fig. 17) from the Uehling CO₂ apparatus. A consideration of the results from the first three tests shows that the so-called radiation loss from the double casing and the bonnet of the furnace was high. If the first test No. A-1 is taken, it appears that in a 12-hour run with an average equivalent register temperature of 149.8 deg. above a 65 deg. F. inlet temperature the heat put into the air passing through the furnace before it left the bonnet amounted to 54 per cent of the total heat in the coal burned.

TABLE 5

SUMMARY OF FIVE COMPLETE PLANT TESTS FOR EFFICIENCY AND CAPACITY OF FURNACE

ITEM	UNCOVERED CASING			Lagged all over	Lagged above Middle Ring A-5
	A-1	A-2	A-3		
Date of test.....	4-23-19	4-30-19	5-1-19	5-3-19	5-9-19
Duration in hours.....	12.0	12.0	9.5	12.0	12.0
Ave. Temp. at Register Faces, deg. F. (actual).....	169.4	182.5	197.7	188.3	175.4
Ave. Temp. at Register Faces, deg. F. (above 65 deg. F.).....	149.8	167.5	186.1	168.8	167.0
Total weight of coal fired, lb.....	256.0	255.0	255.0	255.0	255.0
Total weight of refuse out, lb.....	141.5	107.3	108.5	112.5	114.5
Total equivalent coal in refuse, lb.....	110.0	86.2	86.6	90.0	91.1
Total weight of coal burned, lb.....	146.0	168.8	168.4	165.0	163.9
Rate of combustion, lbs. per sq. ft.....	4.23	4.89	6.16	4.77	4.74
Average chimney draft, inches water.....	0.054	0.054	0.079	0.053	0.058
B.t.u. per lb. coal as received.....	12791	12791	12791	12791	12791
B.t.u. per lb. refuse at end of test.....	10023	10260	10200	10216	10180
Heat developed by coal burned per hr., B.t.u.....	155,500	179,800	226,500	175,900	174,700
Ave. temp. of air at inlet, deg. F.....	84.6	80.0	76.6	84.5	73.4
Ave. bonnet temp., deg. F. (actual).....	181.5	194.8	210.7	200.2	188.0
Ave. temp. rise, inlet to bonnet, deg. F.....	97.0	114.8	134.1	115.7	114.6
Ave. bonnet temp., deg. F. (above 65 deg. F.).....	172.0	179.8	199.1	180.7	179.6
Cu. ft. air entering inlet per hr.....	50,460	53,880	57,120	50,760	52,740
Wt. of air entering inlet per min., lb.....	60.15	65.00	68.30	60.30	64.20
Wt. of air leaving registers per min., lb.....	59.76	67.15	71.16	64.31	68.11
Heat put into air per hr. at bonnet, B.t.u.....	84,200	107,500	132,000	100,500	106,000
Ave. temp. of flue gases, deg. F.....	458	554	676	572	575
Overall efficiency* of furnace, per cent.....	54.20	59.70	58.20	57.20	60.66
Heat loss in dry flue gas, per cent.....	8.82	10.62	12.98	10.85	11.46
Heat loss in water vapor, per cent.....	4.30	3.89	4.16	4.00	4.06
Heat loss by radiation, and unaccounted for, per cent.....	32.68	25.79	25.66	27.95	23.82
Vel. in leaders, ft. per min. 1st floor (average).....	131	148	167	145	144
Vel. in leaders, ft. per min., 2d floor (average).....	226	252	271	257	261
Vel. in leaders, ft. per min., 3d floor (average).....	274	307	332	275†	310
B.t.u. available per sq. in. leader, 1st floor (average).....	67	91	120	89	89
B.t.u. available per sq. in. leader, 2d floor (average).....	104	140	172	143	146
B.t.u. available per sq. in. leader, 3d floor (average).....	142	191	234	165†	192
Barometer, inches mercury.....	29.28	29.43	28.98	29.18	29.37

*These efficiencies are based upon weight of air as measured at inlet, and bonnet temperature corrected for radiation by the method already indicated. See Table 2.

†3d floor leaders dampered.

TABLE 6

SUMMARY OF THE COMPLETE PLANT TEST OF APRIL 23, 1919, FOR EFFICIENCY AND CAPACITY, No. A-1

WARM AIR FURNACE RESEARCH
ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS

Date, 4-23-19

Name, Furnace Staff

Subject, Efficiency and Capacity Test - 150° Equivalent Reg. Temp.

Air Sheet										Bar. 29.28 Hg.		
No.	Leader Size	Register Number	Av. Anemometer Reg./min.	Av. Temp. Deg. F. at Reg.	True Velocity ft./min.	Free Area of Reg. sq ft.	Cu. Ft. of Air per min.	Density	Lb. Air per min.	Distrib. to Each Floor by Wt. %	Stack Velocity ft./min.	Leader Velocity ft./min.
1	12 in	1	89	178.0	159	0.684	108.8	0.0610	6.64			140
2	12 "	3	67	165.0	135	"	92.4	0.06225	5.74			118
3	12 "	7	87	180.5	157	"	107.3	0.0607	6.51	25.02 lb.		138
4	12 "	9 1st Floor	76	170.0	145	"	99.2	0.0617	6.12	41.9 %		128
5	9" sing.	2 2nd Floor	140	161.0	195	0.458	89.4	0.0626	5.59		314	207
7	8" dbl.	4	133	163.8	188	"	86.1	0.0624	5.37		354	253
8	8" sing.	8	118	161.8	172	"	78.8	0.0626	4.94	21.60 lb.	324	232
6	9" dbl.	10	145	165.8	200	"	91.6	0.0622	5.70	36.2 %	321	212
10	9" sing.	5 3rd Fl.	190	167.8	246	"	112.8	0.0619	5.49	13.14 lb.	447	253
12	9" dbl.	6	217	180.4	275	"	126.1	0.0607	7.65	21.9 %	521	295
13							Total		59.76			
14		Inlet	140.5	84.6	152	5.535	841	0.0715	60.15			
15												
16	Reg. No.	Av. Temp. Deg. F. at Boot.	Av. Temp. Drop in Stack	† B.t.u. per min. - min. based on an app. Bar. Reg. Temp. net Temp.			Kind of Stack	Ratio of Stack to Leader Area				
20	1				149	158						
21	3				111	120						
22	7				150	159						
23	9 1st Floor				125.5	134						
24												
25	2 2nd Floor	168.3	7.3		103	120	Single	0.66				
26	4	165.0	1.2		102	113	Double	0.72				
27	8	171.0	9.2		92	109	Single	0.72				
28	10 2nd Floor	171.5	5.7		111	130	Double	0.66				
29												
30	5 3rd Fl.	187.2	19.4		109	141	Single	0.56				
31	6	196.6	16.2		176	216	Double	0.56				

† Wt. of Air $\times .24 (t_R - t_I)$.‡ Wt. of Air $\times .24 (t_B - t_I)$ t_R = Register Temp. t_B = Bonnet Temp. t_I = Inlet Temp.

The heat carried away in the dry flue gases was 8.82 per cent and that lost in water vapor in the flue gases was 2.56 per cent, so that only 65.38 per cent is accounted for. This means that over 34 per cent of the heat value of the coal burned was lost from the furnace casing and bonnet by radiation or in some unaccounted for manner.

Attention should be directed to the fact that in this test the actual weight of air entering the furnace as measured at the inlet was 60.15 lb.

per min. The sum of the weights of air leaving the 10 register faces was 59.76 lb. or only 0.65 per cent less. In all tests, this agreement must be close or else the test must be rejected.

In order to determine the true significance of this radiation loss, a fourth test No. A-4 was run with the same register temperatures as in No. A-2 but with a heavy layer of heat insulation material consisting of $1\frac{1}{2}$ inches of hair felt around the entire furnace and bonnet. The effect of this covering as well as the relation between efficiencies at various register temperatures is shown in the curves of Fig. 18. In

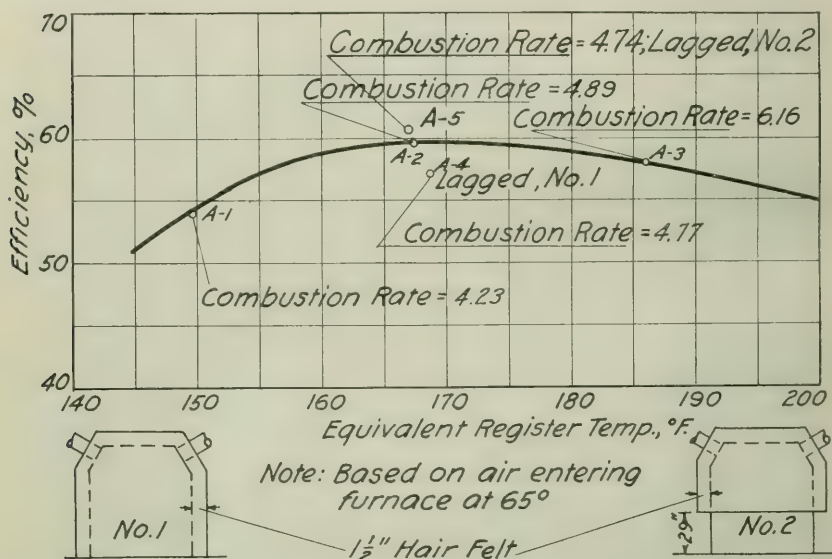


FIG. 18. EFFICIENCY CURVE FOR A FURNACE WHEN INSTALLED AS SHOWN IN FIGS. 15 AND 16, OPERATING AT VARIOUS REGISTER TEMPERATURES, AND RATES OF COMBUSTION

addition to test No. A-4 a fifth test was run with the covering removed from the lower casing section of the furnace, and the results are tabulated and plotted as test No. A-5. No explanation is offered concerning these results until more data are available. It must be clearly understood that each of these tests must be checked by duplicate runs, which may affect the shape of the curves somewhat, but will not materially change their significance. In fact, this curve is so important that check tests should be run over the entire range of register temperatures from 120 to 190 deg. F. at intervals of not more than 10 deg. F.

V. THE AUXILIARY PLANT

In order to make a special study of leaders, stacks, boots, registers and the heat insulation of leaders and stacks, an auxiliary plant (Figs. 19 and 20) has been erected. This plant consists of a single leader and stack connected to a heavily insulated casing 48 inches in diameter, which is equipped with a series of high pressure steam coils. The temperature of the steam and water of condensation is kept under careful observation so that it is readily possible to make an accurate calculation of the air passing through the system since the weight of steam is recorded for every test. This calculation is based on the simple fact that the heat given up by the steam is equal to the heat put into the air except for a very small amount of heat lost by radiation, for which due allowance is made.

The same type of register box and face is used at the head of the stack as is now in service on the main plant. It is, therefore, possible to use the same anemometer calibration and measure the air handled by this single leader and stack at the register as well as by the steam condensed in the coil. The data given (see table in Fig. 20) from the first test on this plant show how well the amounts of air measured by these two methods check each other. This agreement of values is most significant as it shows that there can be no great error in the method involved in the use of a calibrated anemometer in front of a register face.

An elaborate series of tests is now in progress on this plant, and only a few results from the tests so far run are submitted herewith to show the character and value of the information obtainable. These data are based on a study of a second story leader and stack with a 10-inch uncovered leader supplying, (1) a 10-inch round stack, (2) a square stack, (3) a rectangular stack with sides in the ratio of 2:1, and (4) a rectangular stack with sides in the ratio of 4:1. In this first series of tests, the four stacks and the leader all have exactly the same cross-sectional area. The next series of tests will provide for rectangular stacks having first only one-half and secondly three-quarters the area of the leader.

All tests will be run with the same register temperatures for both the full size and for the restricted stacks. By controlling the flow of

steam to the steam coils, various sets of register temperatures are easily obtained.

After these tests have been run the value of covering and the relative efficiency of single and double wall stacks will be determined. It will be noted in the tests reported from the auxiliary plant that the heat loss in the leaders and stacks has been computed as well as the loss in temperature between the bonnet and boot, and again between the boot and register head, for uncovered bright tin pipes.

Additional data will be available for presentation on this part of the work which is in charge of V. S. Day, who will make a separate report on it at the June meeting of the Association.

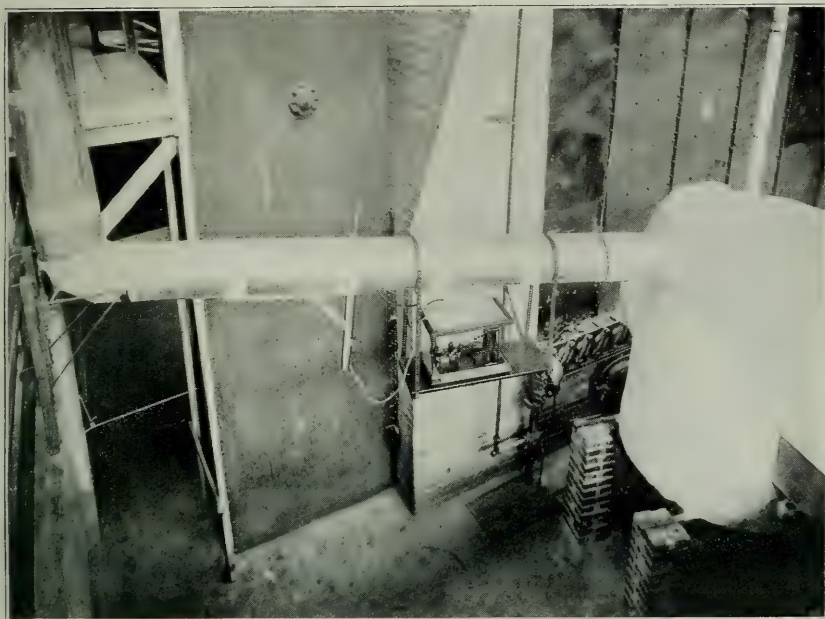


FIG. 19. THE AUXILIARY PLANT SHOWING THE WAHLEN GAGE IN USE ON
A ROUND LEADER AND STACK OF THE SAME AREA

WARM AIR FURNACE RESEARCH
ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS

Date: 5-5-19

Name: V. S. Day

Subject: Results of Tests on Auxiliary Plant with Uncovered 10" Leader and 10" Stack.

Note: Length of Leader 10'-0" and Height of Stack 18'-0"

INST. NO.	TIME	Reqs. Temp.	Inlet Temp.	Diff. Temp.	Equiv. Reqs. Temp.	Temp. Loss in 10' Leader	Temp. Loss in 10' Stack	B.t.u. Loss in 10' Stack	B.t.u. Loss in 10' Stack	B.t.u. Loss in 10' Stack	Total B.t.u. Loss
No.	Date										
1	4-24-19	119.7	70.5	49.2	114.2	3.95	7.33	11.30	12.13	6.55	18.68
2	4-25-19	117.6	72.0	45.6	110.6	4.10	7.10	11.20	12.50	7.22	19.72
3	4-24-19	135.5	70.0	65.5	130.5	4.15	8.65	12.80	11.05	5.30	16.35
4	4-25-19	136.3	72.0	64.3	129.3	4.20	8.80	13.00	11.40	5.43	16.83
5	4-24-19	149.4	71.1	78.3	143.3	5.15	10.72	15.87	11.40	5.47	16.87
6	4-25-19	149.7	72.5	77.1	142.1	5.26	10.83	15.70	11.25	5.61	16.92
7	4-24-19	160.5	72.4	88.1	153.1	6.00	11.45	17.45	10.85	5.68	16.53
8	4-25-19	161.8	72.1	89.7	154.7	6.65	11.95	18.20	10.70	6.16	16.86
9	4-24-19	177.6	70.2	107.4	172.4	19.60	15.80	35.20	11.10	13.90	25.00
10	4-25-19	179.0	72.0	107.0	172.0	16.15	17.00	33.15	12.10	11.50	23.60
11	Date	Reqs. Wt. of Air per hr. from boiler	Vol. of Air per hr. from boiler	Vol. of Air per hr. from boiler	Reqs. Wt. of Air per hr. from boiler	Vol. of Air per hr. from boiler	Vol. of Air per hr. from boiler	Vol. of Air per hr. from boiler	Vol. of Air per hr. from boiler	Vol. of Air per hr. from boiler	Vol. of Air per hr. from boiler
12	4-24-19	119.7	678.0	1475.0	5.11	226.5	4.05	69.2			
13	4-25-19	117.6	753.0	1620.0	5.60	244.0	4.44	71.9			
14	4-24-19	135.5	840.0	1875.0	6.49	323.0	5.13	71.4			
15	4-25-19	136.3	850.0	1900.0	6.55	324.0	5.19	73.7			
16	4-24-19	149.4	891.0	2105.0	7.28	378.0	5.73	71.4			
17	4-25-19	149.7	890.0	2100.0	7.27	374.0	5.74	73.8			
18	4-24-19	160.5	920.0	2140.0	7.40	417.0	5.83	70.2			
19	4-25-19	161.8	952.0	2115.0	7.67	435.0	6.05	72.8			
20	4-24-19	177.6	693.0	1420.0	4.91	322.0	3.85	63.0			
21	4-25-19	179.0	620.0	1496.0	5.18	336.0	4.05	71.3			

† B.t.u. loss in leader in % = $\frac{W \times 24 \times (t_1 - t_2)}{W \times 24 \times (t_1 - t_2)} \times 100$

W = weight of air flowing per hr. based on heat given up by steam less 2%.

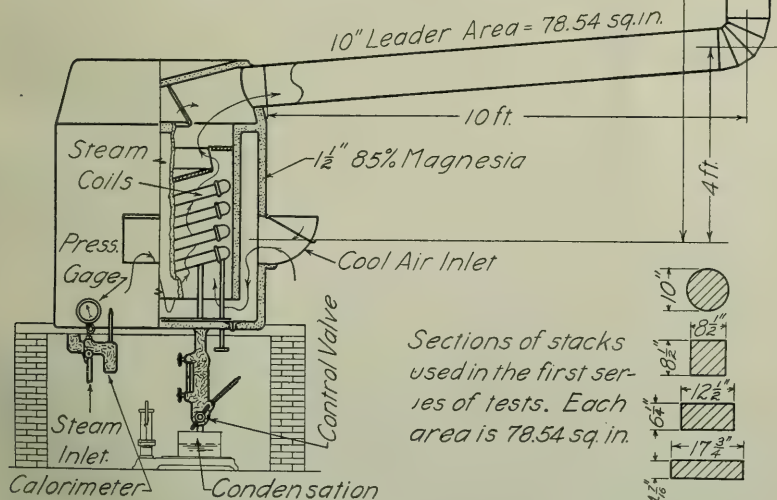


FIG. 20. SECTIONAL ELEVATION OF AUXILIARY PLANT SHOWING STEAM HEATED CASING CONNECTED TO SINGLE LEADER, STACK, AND REGISTER

VI. DISCUSSION OF THE PRESENT PROGRAM OF INVESTIGATION

The objects of this investigation have already been stated in Section I, but it may not be evident from that summary just what the Research Staff has been doing, is now engaged in, and plans to undertake next. For that reason, the following program of activities may help to give a clearer idea of the progress of this work.

(1) A satisfactory method for measuring temperatures at many points had to be developed. This has been done as indicated in Section II and has been in successful operation for several months, and is accurate within 1 or 2 degrees.

(2) The problem of measuring the inflow of cold air at the furnace inlet and the outflow of heated air at numerous register faces occupied a great deal of time. A solution has been found in the method already described in Section III, and the average results are accurate within 1 per cent.

(3) The first actual testing problem was an investigation of the effect of register temperature on the heating and air handling capacity of a complete furnace plant. This work has been done and the results reported in Section IV with a recommendation that for the maximum load conditions in practice the register temperatures should be taken as high as 175 to 185 deg. F., but for average conditions the register temperature should not *exceed* 150 deg. F.

(4) The next actual testing problem was a determination of the variation in efficiency and capacity of a furnace with various register temperatures. This, of course, also involved the effect of various rates of combustion on the efficiency and capacity of a furnace. In no case must the rate of combustion at any time require a draft in excess of 0.2 inch water gage. As hard coal is used, the length of firing period can also be determined. These tests are now in progress and some of the results have been reported and discussed in Section IV.

(5) The heat and air-carrying capacities, and the heat losses of various kinds and sizes of leaders and stacks has long been an open question. Data on losses through various types of boots and registers have also been lacking. All these problems and others involving the length and pitch of leaders as well as the heights of and offsets in stacks are being solved by the tests now in progress with the auxiliary plant. Some of the results of this work are reported in Section V.

(6) A comparison of data on the relative efficiency and capacity of various furnaces of the same grate area and firepot capacity but with different amounts and arrangements of heating surface was one of the first objects suggested by the members of the Association. The tests on a solid firepot, ring-radiator furnace are now in progress. A furnace without radiator having a single combustion chamber will be tested next.

(7) A comparison between hard and soft coal furnaces of the same grate area and firepot capacity should be made as early in this work as possible.

(8) A study of cold air or recirculating connections has been provided for in the present main plant, and data will be taken on the effect of velocities in, and shape of the inlet, as well as the allowable friction loss in the same.

(9) A standard method of rating furnaces is also to be developed as a result of a study of the data secured in the foregoing tests.

(10) Finally, the effect of modifications in design and installation as suggested from a study of the best performance found in these tests should be investigated. It is along this line that the furnace industry must expect to profit most effectively from this work.

VII. APPLICATION OF TEST DATA TO THE DESIGN OF WARM-AIR FURNACE HEATING INSTALLATIONS

It is, of course, necessary to wait until more test data are available before making final recommendations as to the proper procedure, and the most suitable values to use in designing a furnace heating system. It may not, however, be out of place to discuss a simple application of the data so far obtained to a typical furnace heating design problem using such values as are now available. In the following discussion based on the problem presented by W. E. Pratt it has been found necessary to use register temperatures as high as 185 deg. F. for the first floor leaders. It is undoubtedly desirable, however, to use a lower range of register temperatures, with a maximum outlet temperature of not over 175 deg. F., whenever possible.

Curves (Fig. 22) have been plotted from the data obtained in seven tests on the main plant, showing the relation between the register temperatures on any floor, and the B. t. u. carried per square inch of leader pipe per hour to each of these floors.

Knowing the B. t. u. loss per hour from any room on any floor (first, second or third) and given any register temperature, using the value of B. t. u. per square inch of leader pipe from these curves, simple division will give the square inch of leader pipe necessary to heat the room to 70 deg. F., on a zero day.

Taking the first floor rooms of the house plan shown in Fig. 21, and assuming a register temperature for a zero day of 185 deg. F. from the curve for the first floor, it is evident that one square inch of leader pipe will carry 115 B. t. u. per hour to the rooms. Then dividing the B. t. u. loss per hour from the room by 115 gives the number of square inches of leader pipe necessary to heat the room on a zero day.

From the test data (Table 2) it is apparent that the temperature at the registers on the second floor is approximately 10 degrees lower than that on the first floor, or about 175 deg. F. In like manner from the second floor curve it is found that one square inch of leader pipe at this temperature will supply 160 B. t. u. per hour. Dividing the heat loss from the second floor rooms by this value gives the square inches of leader pipe necessary to offset the heat loss from the second floor rooms.

WARM AIR FURNACE RESEARCH

Subject: Register Temperatures & B.t.u. per sq. in. Leader

ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS

Date: 4-29-19

Name: Pratt, W.E.

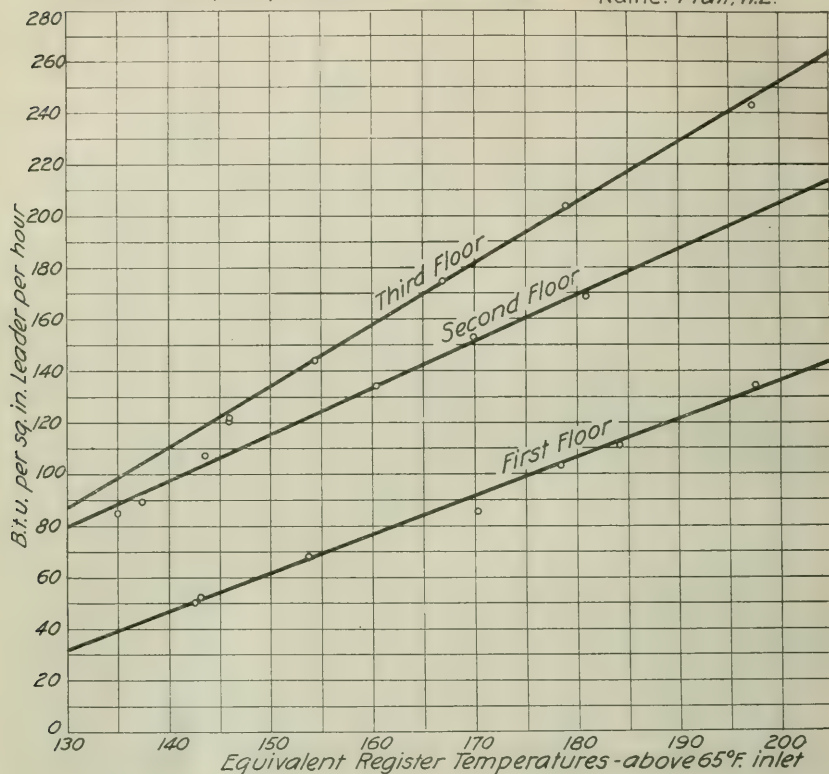


FIG. 22. CURVES SHOWING EFFECT OF REGISTER TEMPERATURE ON LEADER CAPACITY

In like manner the test data show a register temperature on the third floor that is about the same as that on the first floor. From the third floor curve it will be seen that at 185 deg. F. register temperature one square inch of leader pipe will carry 215 B. t. u. per hour. The square inches of leader pipe for the third floor rooms is found as before.

In plotting the curves, the average register temperature for any one floor was used in each case. It will be noted from the typical test data (Table 6) that there is a considerable variation in register temperatures on any one floor. It is therefore evident that the size of the pipe as figured may not be absolutely correct in each case. It is not much

in error, however, and in view of the large increase in pipe areas from one size to the next, the error is negligible for all practical purposes.

It is quite evident that the design of a furnace heating system must be based on the B. t. u. loss per hour from each room. This method of computation is quite familiar to the engineer and can be used by any well qualified furnace man, as fairly simple formulas can be made to cover most types of installation. A later bulletin will cover such applications, and therefore no space is given to the calculation of heat losses here.

It is found that the living room on the first floor of the house under consideration has a heat loss of about 16,600 B. t. u. per hour. With a register temperature of 185 deg. F., each square inch of leader supplies 115 B. t. u. and the calculated area becomes

$$\frac{16,600}{115} = 144 \text{ sq. in.}$$

which requires either one 9-inch and one 10-inch leader, or a special 13½-inch leader.

Following is a table showing the heat loss in B. t. u. per hour from each room of the typical house (Fig. 21), and the size of leader pipe as previously figured. The size leader that would be installed based on the results as figured and the actual areas of same are also given. Stacks are assumed of common commercial sizes as the plant from which the data were secured has the common commercial size stacks. These are approximately 0.7 of the leader area for the second floor, and 0.6 of the leader area for the third floor.

As test data are not yet available on stacks and registers no attempt has been made to discuss the design of this part of the system. It is also assumed that all the preceding leaders are short and straight. The effect of long runs and elbows in leaders is being investigated in tests run on the auxiliary plant.

TABLE 7

HEAT LOSS DATA AND LEADER SIZES FOR A TYPICAL FURNACE PROBLEM

FIRST FLOOR				
Room	B. t. u. Less per Hour	Size Pipe by Test Data Sq. In.	Size Pipe by Install. In.	Area Sq. In.
Living room.....	15590	144	1-9 and 1-10 12 10 12 8*	143
Dining room.....	14040	121		113
Kitchen.....	8980	78		78
Hall.....	11810	103		113
Toilet.....	2287	19		50
SECOND FLOOR				
Bedroom No. 1.....	6990	44	8	50
Bedroom No. 2.....	8670	54	9	64
Bedroom No. 3.....	8335	52	9	64
Bedroom No. 4.....	7245	45	8	50
Bath.....	3254	20	8*	50
THIRD FLOOR (assuming same rooms as second floor)				
Rooms same as second floor with 20 per cent greater heat loss.....	8400 10404 10000 8700 3900	40 48 47 40 18	8 8 8 8 8*	50 50 50 50 50

*No size used commercially less than 8-in. diameter pipe.

VIII. THE ORGANIZATION OF THE FURNACE RESEARCH STAFF AND THE ADVISORY COMMITTEE

The terms of the agreement between the Association and the University provide for a staff composed of at least two full-time research associates and one half-time research assistant working under the supervision of the Engineering Experiment Station. In addition to these men, this work is to be carried on in consultation with an Advisory Committee on Furnace Research appointed by the President of the Association.

It was found impossible to assemble the complete research staff at the time the coöperative agreement became effective, and it was not until October 17, 1918, that the first man reported for duty. In the meantime a large amount of preliminary work had been done by Professors Willard and Kratz in getting the original plant equipped and in developing the calibrating plants. As soon as Prof. S. L. Simmering arrived, F. G. Wahlen was detailed to assist him, and Professor Kratz has devoted an increasing amount of his time to the work since October 1. With the addition of V. S. Day on December 18, 1919, and finally of W. E. Pratt on January 16, 1918, a very effective organization has been perfected and the work has been progressing rapidly and effectively, since January of this year. It should also be noted that at all times there have been available one or more machinists and mechanics of the Mechanical Engineering Department as well as F. W. Stearns (special mechanic) who has been of the greatest assistance in taking data on many tests. In the operation of the main plant on a complete 10 to 12 hour test at least five men are absolutely necessary.

The personnel of the Research Staff has been made up as given on the following page.

FURNACE RESEARCH STAFF

DEAN C. R. RICHARDS . . .	<i>Dean College of Engineering and Director Engineering Experiment Station.</i>
PROFESSOR A. C. WILLARD . . .	<i>Professor Heating and Ventilation</i>
PROFESSOR A. P. KRATZ	<i>Research Assistant Professor</i>
PROFESSOR S. L. SIMMERING*	<i>Research Associate</i>
MR. F. G. WAHLEN	<i>Research Graduate Assistant</i>
MR. V. S. DAY†	<i>Research Assistant and Acting Secretary</i>
MR. W. E. PRATT‡ . . .	<i>Special Investigator and Research Associate</i>

The Advisory Committee held its first meeting at the University on December 17, 1918. R. C. Cook was unable to be present at this meeting, and W. A. Tuerre represented Walter Wimmer. Since then, both J. M. McHenry and P. J. Dougherty have been frequent visitors at the University and have kept in close touch with the progress of the work. The present program of investigation as given in Section VI of this Bulletin was outlined at the time of this meeting in joint conference with the members of the research staff. The complete organization of this committee follows:

ADVISORY COMMITTEE ON FURNACE RESEARCH

MR. J. M. MCHENRY, <i>Chairman</i> <i>Manager of the Furnace Department</i> <i>Detroit Stove Works</i> <i>Detroit, Michigan.</i>
MR. P. J. DOUGHERTY, <i>Heating Engineer, International Heater Company,</i> <i>Utica, New York.</i>
MR. R. C. COOK, <i>Manager, Thatcher Furnace Company</i> <i>Chicago, Illinois.</i>
MR. WALTER WIMMER, <i>Manager, Furnace Department</i> <i>Wrought Iron Range Company</i> <i>St. Louis, Missouri.</i>
MR. E. S. MONCRIEF, <i>Vice-President, The Henry-Miller Foundry Company</i> <i>Cleveland, Ohio.</i>

*Appointed October 18, 1918. Resigned March 31, 1919.

†Appointed December 18, 1918.

‡Appointed January 16, 1919.

IX. RECOMMENDATIONS TO THE ASSOCIATION CONCERNING THE FUTURE OF THIS INVESTIGATION

The work so far accomplished has already shown that a great many factors vitally affecting the design and operation of furnaces and furnace heating systems have not only not been determined but their effect has not even been correctly estimated. The unusual difficulties encountered in the accurate measurement of the air flowing through such a system under natural conditions have proved the most serious obstacle in this undertaking. Enough testing work has been done, however, to show that most of the undetermined factors referred to can be measured, and the results interpreted in such form as to be of practical use to the furnace industry, as set forth in the preceding pages of this Bulletin.

It is therefore recommended that this investigation should be continued under the same terms as those of the present coöperative agreement which expires October 1, 1919. It is further suggested that if a new agreement is entered into after October 1, 1919, it will be well to consider the desirability of providing for an advisory engineering service for the benefit of all members of the Association. Such a service would include the interpretation of the results of this investigation in the solution of problems in furnace design and rating and in the layout and installation of furnace heating systems.

APPENDIX I—FINANCIAL STATEMENT

Expenditures by the National Warm Air Heating and Ventilating Association since Oct. 1, 1918**A. Salaries:**

1. S. L. Simmering*	\$1100
Oct. 18 to April 1	
2. V. S. Day	448
Dec. 17 to May 1	
3. W. E. Pratt	800
Jan. 16 to May 1	
Total	<u>\$2348.00</u>

B. Labor:

1. For mechanics' labor on plant:	
Total	354.00

C. Materials† (This includes labor for work done in shops other than the testing laboratory)

Coal, furnace work, instruments, auxiliary plant, etc.:	
Total	<u>1053.35</u>
Grand total	3755.35

Total expenditure	3755.36
Fund appropriated	8000.00
Remainder, unexpended, May 1, 1919	<u>\$4244.64</u>

Expenditures by the University since January 1, 1917**A. Salaries:‡**

1. A. P. Kratz	\$1200.00
(Estimated at approximately half time for one year)	
2. F. G. Wahlen	<u>350.00</u>
Total	\$1550.00

B. Labor:

Draftsmen and Mechanics	700.00
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C. Main Plant:

Materials and Labor	886.58
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D. Instruments:§	225.62
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E. Calibrating Plants:

Materials and Labor	<u>132.85</u>
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Grand total	<u>\$3495.05</u>
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*Resigned March 31, 1919.

†Present furnace and piping donated by members of the Association.

‡This does not include any charges for supervision by A. C. Willard.

§Not inclusive of instruments supplied from the instrument room of the Mechanical Engineering Laboratory.

This list does not include charges for materials drawn from University stock.

APPENDIX II—THE AGREEMENT BETWEEN THE ASSOCIATION AND THE UNIVERSITY

ARTICLES OF AGREEMENT between the National Warm-Air Heating and Ventilating Association and the Board of Trustees of the University of Illinois for a co-operative investigation of Warm-Air Furnaces and Furnace Heating Systems by the Engineering Experiment Station of the University of Illinois under the following terms and conditions:

I. This agreement is executed for a period of one year beginning October 1, 1918, with the understanding that it may be extended for additional similar periods under the same or such other terms as may be mutually agreed upon.

II. The Engineering Experiment Station will supervise and direct all testing work and the computation of all results obtained; it will furnish the furnace testing plant now installed in the Mechanical Engineering Laboratory, together with all testing instruments necessary in the investigation. Should important changes in or additions to the present testing plant become necessary, it is agreed that the cost thereof shall be charged against the fund provided by the National Warm-Air Heating and Ventilating Association for the general investigation as hereinafter provided.

III. An advisory committee of the National Warm-Air Heating and Ventilating Association shall be appointed to consult with the officers of the Engineering Experiment Station concerning the conduct of the investigation and the general testing program to be undertaken. When a general program of tests has been agreed upon, the conduct of the tests shall be entirely under the control of the Engineering Experiment Station, which is necessarily responsible for the results secured.

IV. All of the original test data and the computations and results of the investigation are to be the property of the Engineering Experiment Station and they are to be kept on file at the University of Illinois. Furthermore, it is understood and agreed that the Engineering Experi-

ment Station shall have the exclusive right to publish the results of the tests and investigations conducted under this agreement, and no publicity to any of the tests shall be given prior to the publication of the results by the Engineering Experiment Station.

V. The advisory committee or other authorized representative of the National Warm-Air Heating and Ventilating Association shall at all times have access to the data secured and the computed results, and one copy thereof shall be furnished the Secretary of the National Warm-Air Heating and Ventilating Association subject, however, to the conditions named in Article IV. The Engineering Experiment Station will submit a semi-annual report on the work in progress, in addition to the data and results, to the National Warm-Air Heating and Ventilating Association.

VI. Not less than two full time testing assistants and one half-time assistant will be needed to conduct the investigation herein contemplated. The salaries of these assistants and of any other assistants later found necessary are to be paid from the funds provided by the National Warm-Air Heating and Ventilating Association. These assistants are to be considered members of the staff of the Engineering Experiment Station during their connection therewith.

VII. All furnaces tested are to be furnished and erected at the testing plant without expense to the Engineering Experiment Station. All expenses connected with the preparation of the furnaces for testing and any other expense connected with these tests, not otherwise provided for, shall be paid from the funds furnished by the National Warm-Air Heating and Ventilating Association.

VIII. On or before October 10, 1918, the National Warm-Air Heating and Ventilating Association shall pay to the Board of Trustees of the University of Illinois an initial sum of two thousand dollars (\$2,000.00) and thereafter it shall maintain in this special fund for furnace testing a balance of not less than five hundred dollars (\$500.00) to be administered by the Comptroller of the University and paid out by him on vouchers approved by the Director of the Engineering Experiment Station. It is further agreed that the total amount of the fund expended by the National Warm-Air Heating and Ventilating Association shall not exceed eight thousand dollars (\$8,000.00) for the first

year of this agreement. At the termination of this agreement or at any time on the request of the Association, the Comptroller shall render an accounting to the National Warm-Air Heating and Ventilating Association, and he shall return to the Association any unexpended balance which may remain in this fund at the termination of this agreement.

The Board of Trustees of the University of Illinois

[Signed]

Lloyd Morey, Comptroller.

Allen W. Williams,

Secretary, N. W. A. H. & V. A.

Witnesses: *H. E. Cunningham*,

Secretary, University of Illinois.

Bess D. Fritz.

LIST OF PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION

- Bulletin No. 1.* Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904. *None available.*
- Circular No. 1.* High-Speed Tool Steels, by L. P. Breckenridge. 1905. *None available.*
- Bulletin No. 2.* Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905. *None available.*
- Circular No. 2.* Drainage of Earth Roads, by Ira O. Baker. 1906. *None available.*
- Circular No. 3.* Fuel Tests with Illinois Coal (Compiled from tests made by the Technological Branch of the U. S. G. S., at the St. Louis, Mo., Fuel Testing Plant, 1904-1907), by L. P. Breckenridge and Paul Diserens. 1908. *Thirty cents.*
- Bulletin No. 3.* The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906. *None available.*
- Bulletin No. 4.* Tests of Reinforced Concrete Beams, Series of 1905, by Arthur N. Talbot. 1906. *Forty-five cents.*
- Bulletin No. 5.* Resistance of Tubes to Collapse, by Albert P. Carman and M. L. Carr. 1906. *None available.*
- Bulletin No. 6.* Holding Power of Railroad Spikes, by Roy I. Webber. 1906. *None available.*
- Bulletin No. 7.* Fuel Tests with Illinois Coals, by L. P. Breckenridge, S. W. Parr, and Henry B. Dirks. 1906. *None available.*
- Bulletin No. 8.* Tests of Concrete: I, Shear; II, Bond, by Arthur N. Talbot. 1906. *None available.*
- Bulletin No. 9.* An Extension of the Dewey Decimal System of Classification Applied to the Engineering Industries, by L. P. Breckenridge and G. A. Goodenough. 1906. Revised Edition 1912. *Fifty cents.*
- Bulletin No. 10.* Tests of Concrete and Reinforced Concrete Columns, Series of 1906, by Arthur N. Talbot. 1907. *None available.*
- Bulletin No. 11.* The Effect of Scale on the Transmission of Heat through Locomotive Boiler Tubes, by Edward C. Schmidt and John M. Snodgrass. 1907. *None available.*
- Bulletin No. 12.* Tests of Reinforced Concrete T-Beams, Series of 1906, by Arthur N. Talbot. 1907. *None available.*
- Bulletin No. 13.* An Extension of the Dewey Decimal System of Classification Applied to Architecture and Building, by N. Clifford Ricker. 1907. *None available.*
- Bulletin No. 14.* Tests of Reinforced Concrete Beams, Series of 1906, by Arthur N. Talbot. 1907. *None available.*
- Bulletin No. 15.* How to Burn Illinois Coal without Smoke, by L. P. Breckenridge. 1908. *None available.*
- Bulletin No. 16.* A Study of Roof Trusses, by N. Clifford Ricker. 1908. *None available.*
- Bulletin No. 17.* The Weathering of Coal, by S. W. Parr, N. D. Hamilton, and W. F. Wheeler. 1908. *None available.*
- Bulletin No. 18.* The Strength of Chain Links, by G. A. Goodenough and L. E. Moore. 1908. *Forty cents.*
- Bulletin No. 19.* Comparative Tests of Carbon, Metallized Carbon and Tantalum Filament Lamps, by T. H. Amrine. 1908. *None available.*
- Bulletin No. 20.* Tests of Concrete and Reinforced Concrete Columns, Series of 1907, by Arthur N. Talbot. 1908. *None available.*
- Bulletin No. 21.* Tests of a Liquid Air Plant, by C. S. Hudson and C. M. Garland. 1908. *Fifteen cents.*
- Bulletin No. 22.* Tests of Cast-Iron and Reinforced Concrete Culvert Pipe, by Arthur N. Talbot. 1908. *None available.*
- Bulletin No. 23.* Voids, Settlement and Weight of Crushed Stone, by Ira O. Baker. 1908. *Fifteen cents.*
- *Bulletin No. 24.* The Modification of Illinois Coal by Low Temperature Distillation, by S. W. Parr and C. K. Francis. 1908. *Thirty cents.*
- Bulletin No. 25.* Lighting Country Homes by Private Electric Plants, by T. H. Amrine. 1908. *Twenty cents.*

*A limited number of copies of bulletins starred is available for free distribution.

Bulletin No. 26. High Steam-Pressure in Locomotive Service. A Review of a Report to the Carnegie Institution of Washington, by W. F. M. Goss. 1908. *Twenty-five cents.*

Bulletin No. 27. Tests of Brick Columns and Terra Cotta Block Columns, by Arthur N. Talbot and Duff A. Abrams. 1909. *Twenty-five cents.*

Bulletin No. 28. A Test of Three Large Reinforced Concrete Beams, by Arthur N. Talbot. 1909. *Fifteen cents.*

Bulletin No. 29. Tests of Reinforced Concrete Beams: Resistance to Web Stresses, Series of 1907 and 1908, by Arthur N. Talbot. 1909. *Forty-five cents.*

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**Bulletin No. 31.* Tests with House-Heating Boilers, by J. M. Snodgrass. 1909. *Fifty-five cents.*

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Bulletin No. 35. A Study of Base and Bearing Plates for Columns and Beams, by N. Clifford Ricker. 1909. *Twenty cents.*

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Bulletin No. 37. Unit Coal and the Composition of Coal Ash, by S. W. Parr and W. F. Wheeler. 1909. *None available.*

Bulletin No. 38. The Weathering of Coal, by S. W. Parr and W. F. Wheeler. 1909. *Twenty-five cents.*

**Bulletin No. 39.* Tests of Washed Grades of Illinois Coal, by C. S. McGovney. 1909. *Seventy-five cents.*

Bulletin No. 40. A Study in Heat Transmission, by J. K. Clement and C. M. Garland. 1910. *Ten cents.*

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**Bulletin No. 45.* The Strength of Oxyacetylene Welds in Steel, by Herbert L. Whittimore. 1911. *Thirty-five cents.*

**Bulletin No. 46.* The Spontaneous Combustion of Coal, by S. W. Parr and F. W. Kressman. 1911. *Forty-five cents.*

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**Bulletin No. 49.* Tests of Nickel-Steel Riveted Joints, by Arthur N. Talbot and Herbert F. Moore. 1911. *Thirty cents.*

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Bulletin No. 51. Street Lighting, by J. M. Bryant and H. G. Hake. 1912. *Thirty-five cents.*

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**Bulletin No. 56.* Tests of Columns: An Investigation of the Value of Concrete as Reinforcement for Structural Steel Columns, by Arthur N. Talbot and Arthur R. Lord. 1912. *Twenty-five cents.*

**Bulletin No. 57.* Superheated Steam in Locomotive Service. A Review of Publication No. 127 of the Carnegie Institution of Washington, by W. F. M. Goss. 1912. *Forty cents.*

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**Bulletin No. 58.* A New Analysis of the Cylinder Performance of Reciprocating Engines, by J. Paul Clayton. 1912. *Sixty cents.*

**Bulletin No. 59.* The Effect of Cold Weather upon Train Resistance and Tonnage Rating, by Edward C. Schmidt and F. W. Marquis. 1912. *Twenty cents.*

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**Bulletin No. 61.* Characteristics and Limitation of the Series Transformer, by A. R. Anderson and H. R. Woodrow. 1913. *Twenty-five cents.*

Bulletin No. 62. The Electron Theory of Magnetism, by Elmer H. Williams. 1913. *Thirty-five cents.*

Bulletin No. 63. Entropy-Temperature and Transmission Diagrams for Air, by C. R. Richards. 1913. *Twenty-five cents.*

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Bulletin No. 67. Reinforced Concrete Wall Footings and Column Footings, by Arthur N. Talbot. 1913. *Fifty cents.*

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Bulletin No. 69. Coal Washing in Illinois, by F. C. Lincoln. 1913. *Fifty cents.*

Bulletin No. 70. The Mortar-Making Qualities of Illinois Sands, by C. C. Wiley. 1913. *Twenty cents.*

Bulletin No. 71. Tests of Bond between Concrete and Steel, by Duff A. Abrams. 1914. *One dollar.*

**Bulletin No. 72.* Magnetic and Other Properties of Electrolytic Iron Melted in Vacuo, by Trygve D. Yensen. 1914. *Forty cents.*

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Bulletin No. 76. The Analysis of Coal with Phenol as a Solvent, by S. W. Parr and H. F. Hadley. 1914. *Twenty-five cents.*

**Bulletin No. 77.* The Effect of Boron upon the Magnetic and Other Properties of Electrolytic Iron Melted in Vacuo, by Trygve D. Yensen. 1915. *Ten cents.*

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PANEL SYSTEM OF COAL MINING
A GRAPHICAL STUDY OF PERCENTAGE
OF EXTRACTION

BY

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PANEL SYSTEM OF COAL MINING

A GRAPHICAL STUDY OF PERCENTAGE OF EXTRACTION

I. INTRODUCTION

1. *Reasons for the Investigation.*—In 1917 an investigation* of the percentages of coal extracted and lost in Illinois and in other bituminous coal mining districts showed that the percentage obtained is less than is commonly believed. The conclusions reached in the earlier investigation naturally led to the study of the panel system to determine the greatest possible extraction with different dimensions of workings.

2. *Other Investigations.*—Investigations of a similar nature have been made to determine the relation between dimensions of workings and amounts of extraction. Special mention should be made of the work of J. C. Quade, G. E. Lyman, and J. C. Gibson, whose methods are described on pages 46, 66, and 70. So far as is known, however, no study of the panel system in general with regard to the percentage of extraction and the change of this percentage with change of dimensions of workings has hitherto been made.

3. *Acknowledgments.*—The work of the Illinois Coal Mining Investigations is carried on under the direction of Professor H. H. STOEK, head of the Department of Mining Engineering, University of Illinois; F. W. DE WOLF, Chief, State Geological Survey Division; and G. S. RICE, Chief Mining Engineer, U. S. Bureau of Mines. Professor Stoek has been especially helpful in carefully revising the manuscript.

4. *Summary.*—The investigation shows that the highest extraction which can possibly be attained under the conditions assumed, with rooms 300 feet long and 30 feet wide on 50-foot centers, is only 57.05 per cent. Even if the improbable ratio of room to pillar width

*Young, C. M., "Percentage of Extraction of Bituminous Coal with Special Reference to Illinois Conditions." Illinois Coal Mining Investigations, Univ. of Ill. Eng. Exp. Sta., Bul. 100, 1917.

of 4 to 1 (40-foot rooms on 50-foot centers) is assumed, the highest attainable extraction is 68.48 per cent. No better results than these can be reached unless the amount of coal left in room pillars or in barrier pillars is reduced. As a matter of fact, the average extraction throughout the State is not more than 50 per cent and in those parts where coal is thickest and lies at greatest depth, the extraction will not average so much. The lowest extractions are due in part to the leaving of top coal; thus the actual extraction in some districts is lower than that indicated by calculation on an area basis.

The percentage of extraction increases with the increase of ratio between room width and pillar width, with length of rooms and with number of rooms per entry, but the diagrams showing the effect of changes of dimensions on percentages of extraction indicate that, except in the case of ratio of room width to pillar width, very nearly the maximum effect of these changes has been reached by the dimensions considered, *i. e.*, room length from 200 to 300 feet, room width from 20 to 40 feet, number of rooms per entry from 8 to 24. Further increase of length of rooms or of number of rooms per entry would not materially increase the percentage of extraction.

The percentage of extraction could be further increased by increase of room width in relation to pillar width, but it is only rarely that a ratio of even 4 to 1 can be used without the production of squeezes. The conclusion is, therefore, warranted that the extraction under a panel system of mining, which relies upon coal left in the ground for the support of the overburden, cannot be greater than about 68 per cent unless a smaller amount of coal is left in the form of barrier pillars than is assumed in this investigation.

5. *Reasons for Low Extraction.*—There are two essential reasons for low extraction. The first is the leaving of top coal, because the roof needs support or because the bed is too thick for convenient mining of the whole thickness. Such losses occur principally in the thick coal of the southern part of the State. When some support for the roof is necessary and when it can be furnished by coal left in place at less cost than by artificial means, the leaving of coal is justified, commercially, though such loss may still be criticized from the standpoint of conservation. In some places, however, the thickness of coal left is much greater than is necessary to support the roof, and it is probable that a considerably larger amount of the coal might be extracted at a cost which would allow a profit on the top coal mined.

The second reason for low extraction lies in the method of mining which depends upon coal, left in the form of pillars, to support overlying material. The use of coal for such support may be considered: first, for the support of the immediate top until a place has been worked out, and secondly, for the permanent support of the overburden to prevent subsidence of the surface.

In the first case large pillars would commonly be unnecessary and the ratio of room width to pillar width might be large. Under this case may be considered such operations as those in Fulton County, discussed in Appendix I, where no attempt is made at permanent support of the surface, and where coal left in pillars may be considered as serving the same purpose as props. Pillars which are 8 feet wide near the entry are tapered to almost nothing at the end; yet these pillars serve their purpose of support to the immediate top until the coal has been worked out. Under such circumstances it is possible to extract from 70 to 80 per cent of the coal, but such results would be unattainable in thick coal because the strength of a pillar decreases rapidly as its height increases, and consequently greater pillar width would be necessary to furnish the support needed.

The second case is that of the use of coal in the form of pillars as a permanent support for the overburden, and this use constitutes the principal reason for low extraction. A much higher percentage of coal might be obtained if the surface were allowed to subside. Under present conditions, however, this practice is not often considered practical, especially where ownership of the coal and the surface is separate, because the operator is often compelled to pay very high damages for any disturbance of the surface.

While no general rule can be stated for the determination of the dimensions of pillars and of the ratio of pillar area to room area necessary for the permanent support of the surface at a given depth, it is known that the relative area of pillars must be made greater as the depth increases. Experience in Illinois shows that the surface cannot be permanently sustained over the deeper and thicker beds of the State unless about half of the coal is left. This statement is true in general for Districts V, VI, and VII, of the Illinois Coal Mining Investigations, which include bed 5 in Saline and Gallatin counties and nearly all mines in the No. 6 coal.

No high percentage of extraction is possible without subsidence of the surface unless the space left by the coal is filled, probably by washing fine material into the mine through pipes. Illinois mines are

in general nearly level and it would be difficult to transport the filling material along the entries by means of water; also the removal of the water would be difficult and expensive. For these reasons the method appears at present to be impractical in Illinois; therefore if high extraction is to be obtained subsidence must be expected and controlled as is being successfully done in some districts where extraction of more than 90 per cent is customary.

II. ADVANTAGES OF GREATER EXTRACTION

The principal advantages of higher extraction may be summarized as follows:

6. *Investment per Ton of Total Output.*—If the amount of coal extracted could be increased from 50 to 100 per cent, the investment, per ton of total coal produced for surface plants, shafts, entries, etc., would be reduced by half because twice as much coal would be handled with the equipment. Maintenance charges, however, would not be similarly reduced since the colliery would be in operation for twice as long if the same territory were involved. The cost per ton of coal in the ground would be decreased by one-half when the coal is purchased in fee, and where it is leased on royalty the owner of the land would receive twice as much as he formerly received.

7. *Cost of Haulage.*—The cost per ton for moving the coal from the working place to the shaft would be decreased, because the average length of haul would be only half as much as with 50 per cent extraction. Twice as much coal would be hauled through the entries, so that the cost per ton of coal for maintaining entries would be lessened. Since the element of time is also involved, it is not possible to say that the cost for maintenance would be reduced by 50 per cent.

8. *Cost of Ventilation.*—The average distance from the shaft of places to be ventilated being only half as much as with 50 per cent extraction, the expense of ventilation would be decreased. Ventilation would be simplified, because worked-out places would cave and would require no attention except the provision of bleeders or of seals.

To summarize, the cost per ton of total coal for all installations and excavations which would not need renewal because of the increased time of service would be reduced by 50 per cent. In operations whose costs are affected by the distance from the shafts to the point of production, the costs would be reduced in proportion to the effect of the distance. While it cannot be expected that an extraction of 100 per cent will be obtained, an extraction of 90 per cent should not be

difficult from an engineering standpoint, and the economies resulting would be in proportion to the increase.

9. *Efficiency of Supervision.*—Appreciation of the need of thorough supervision to preserve mines in working condition and to prevent accidents is increasing, but under present mining practice the visits to a working place can be made more frequent only by increasing the supervising force, thus adding to the cost of coal. With greater extraction the concentration of workings would eliminate a part of the time now lost in travel, and thus would help to solve the problem of increased supervision.

10. *Prevention of Waste.*—The greatest ultimate advantage of higher extraction would be the increase of the available reserves of coal. At present this advantage is largely overlooked, because the reserves of coal of the quality and thickness now mined are sufficient for many years. Unfortunately, however, it is the best coal and that easiest to produce which is being lost, and the coal which will be available when the reserves are exhausted will certainly be more costly and perhaps not so good. Even if the question of reserves is neglected because no immediate exhaustion is possible, it is a subject for great regret that a substance as valuable as coal should be unnecessarily lost.

There is no doubt of the ability of mining engineers to plan operations to get high extraction. The methods are well known and are employed with great advantage and without great difficulty in some districts, and there is no reason to doubt their success in Illinois. The problem is more one of immediate commercial advantage than one of engineering practice.

III. PRINCIPLES INVOLVED IN HIGH EXTRACTION

High extraction requires the mining of pillar coal. Three principles are involved in the successful extraction of this coal: first, the strain on the roof above the rooms must not be great enough to cause the roof to fall before the pillar coal is removed; secondly, the strain on the pillars must not be great enough to cause squeezing; thirdly, additional strain on the pillars, due to pillar drawing, must be prevented by the breaking of the roof behind the retreating pillar face.

The fall of the roof can be prevented by making the room sufficiently narrow, or at least the strain can be decreased so that proper timbering will prevent falls. This does not necessarily involve low ratio of room width to pillar width. If the pillars are to be removed, however, they will necessarily be made large enough for convenient working. In some districts where pillar coal is successfully mined and where high extraction is reached, rooms are made very narrow and are, in fact, little more than openings for ventilation and for access to the pillar coal. Such extreme narrowness is necessary only under bad top, and rooms in most places in Illinois could probably be made 20 feet wide without interference with successful pillar work.

The strain on the pillars due to the weight of the overburden must be kept within the limits of strength of the pillars themselves and of the top and bottom. When the room coal is removed, the weight of the overlying material is transferred to the pillars and these must be made large enough to stand the strain without being crushed or pressed into the top or bottom.

When the extraction of the pillar coal is commenced at the end of the room, a part of the weight of the overburden above the portion removed is transferred to the remaining pillars, thus increasing the strain. This strain may be relieved by the breaking of the roof behind the retreating pillar face.

If enough coal is left in pillars to prevent crushing before pillar drawing begins, and if the strain is relieved by the breaking of the roof during pillar drawing, squeezes will be entirely prevented.

These three principles: rooms narrow enough for the support of the roof, pillars large enough to stand without crushing, and

relief of additional strain due to pillar drawing by the breaking of the roof, are successfully applied in some mining districts in this country. There is nothing in the physical conditions of the Illinois coal fields to indicate that the application of these principles is impossible or even unusually difficult. •

IV. METHOD OF INVESTIGATING THE PERCENTAGES OF EXTRACTION

The object of the calculations hereinafter described was the determination of percentages of extraction when plans for the development of a mine are carefully made and all dimensions accurately followed. It was necessary to consider a hypothetical mine or a part of one consistently developed on some predetermined plan. The discussion has been confined to the panel system, because it represents the highest development reached in the extraction of coal by rooms and pillars. It is upon this system that all large modern mines in Illinois are projected.

The term *panel system* originally implied the isolation of a group of rooms, called a panel, from other such groups or panels, by a surrounding pillar of coal pierced on one side only by the room entries. The term is now frequently applied to a system in which the room entries do not terminate in the panel but are driven through to the next cross entry, the block of rooms thus being opened at both ends instead of only at one, the pillars between the ends of panels being omitted.

The present tendency in Illinois seems to be toward the adoption of a more nearly completely isolated panel than has been used though the fire pillars remaining are too narrow to resist squeezing. On this basis the values in the tables and diagrams given have been calculated. The assumed pillars between the ends of adjacent panels are, however, very thin and approximately the same values will be found if these pillars are omitted. The figures and diagrams will apply very closely to either form of the panel system.

11. *Basis of Calculation.*—In the following discussion extraction is calculated on the basis of area excavated instead of on that of tonnage produced. When the workings are of uniform height throughout the mine, the extraction on the basis of tonnage is proportional to that on the basis of area, but, if a portion of the coal is left at top or bottom as is frequently the case in thick coal and under a poor roof, the ratio of tonnage to area may vary in different parts of the mine. Whenever coal is left on the top or bottom, the extraction on a tonnage basis is less than that on an area basis. To get the per-

centage of extraction on a tonnage basis from that on an area basis, the latter should be multiplied by the ratio of thickness mined to the total thickness of the bed. In some parts of Illinois, for example, where the thickness of the coal is nine feet or more, only about seven feet of the coal is extracted. In such places the tonnage produced cannot be more than seven-ninths, or 78 per cent, of that indicated by the area excavated and is less if the thickness of the coal is greater than nine feet. This fact should be borne in mind in considering the percentages of extraction given in this bulletin. In other words these percentages are the maximum amounts of coal which it is possible to get with the given dimensions of workings without the gouging of pillars or the extraction of pillar coal on the retreat. As there is always some waste in mining, the extractions obtained in practice with similar dimensions may be expected to fall below those indicated in the tables. The amount of waste is variable, but it is doubtful if it is ever less than 5 per cent.

12. *Method of Computation.*—An area of 160 acres was selected as large enough to give sufficiently accurate results, and workings were laid out for this area. Since an area of nearly an acre is worked out per day in the larger mines, which produce 4000 tons, or more, per day as now operated in Illinois, it will be seen that 160 acres is only a small part of the tract developed by a single large mine; in fact it represents only about 160 days' work. Accordingly in planning the projection, no attempt was made to lay out 160 acres as a complete mine, but this small tract was assumed to be part of a larger district and was treated as if a square of 160 acres had been taken from the map of a large mine.

If the 160 acres had been developed by itself, one would naturally assume that the main entry was driven through the middle of the tract and that the cross entries were driven equal distances to each side. Instead of this assumption it was determined as a matter of simplification that the line of the ends of a series of panels driven from one cross entry should constitute one border, $m-n$, and the sides of a series of panels should constitute another border, $n-o$ (Fig. 1).

In this 160-acre tract workings were laid out with different dimensions and the percentages of extraction for these different dimensions calculated. The room lengths chosen were 200 feet, 250 feet, and 300 feet. The numbers of rooms per entry chosen were 8, 12, 16,

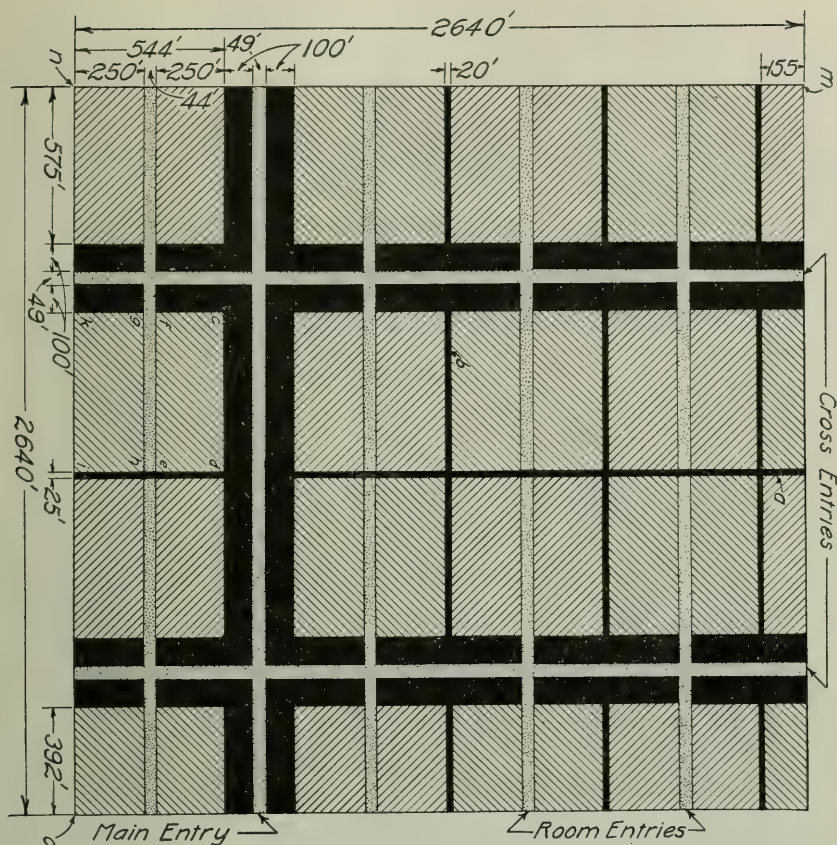


FIG. 1. MAP OF 160-ACRE TRACT SELECTED FOR INVESTIGATION

20, 24, and 28. The cases assumed include, of course, only a few of the many dimensions and numbers of rooms that may occur, but they show the effects of variation in dimensions and number.

For the first calculation it was assumed that all rooms should be 25 feet wide and driven on 50-foot centers. After the method had been developed for these dimensions, calculations were made for different room widths, namely, 20, 30, 35, and 40 feet. Other assumptions made with regard to various portions of the workings will be explained in the detailed consideration of the calculations of area and extraction.

No allowance was made for a barrier pillar around the tract

since the barrier pillar left around the borders of a mine constitutes only a very small percentage of the total area, and the proportion which would be chargeable to an area of 160 acres would be insignificant.

One result of the limitation of the area is the occurrence of certain irregularities in the percentages of area occupied by different portions of the workings and in the percentages of extraction. These irregularities would not be found if a larger tract were under consideration. They will be explained in the discussion of the diagrams showing areas and percentages of extraction (Figs. 4 to 9).

The dimensions assumed are as follows:

	Feet
Entry width	12
Main entry pillar	25
Cross entry pillar	25
Room entry pillar	20
Entry cross-cut width	12
Entry cross-cut centers	72
Barrier pillars	100
Pillars at sides of panels	20
Pillars at ends of panels	25
Room neck, width	18
Room neck, length	12
Distance from entry rib to point where room reaches full width	18
Room cross-cut width	18

The constant quantities in the calculations are the dimensions of the tract under consideration, the widths of entries and entry pillars, the spacing and width of entry cross-cuts and room cross-cuts, the dimensions of room necks, and the widths of barrier pillars and of pillars at sides and ends of panels. The variables are the length of rooms, the width of rooms, and the number of rooms per panel. Changes in these variables involve changes in the percentages of area occupied by different portions of the workings and in the percentage of extraction in the portions occupied by rooms and pillars.

13. *Method of Procedure.*—The method of procedure involved: first, the determination of the percentage of coal won or lost in any portion of the workings, such as rooms and pillars, and barriers, and secondly, the determination of the percentage of the entire area

occupied by this portion. A calculation was made, for example, of the percentage of extraction inside a panel and then of the percentage of the total area occupied by panels. A summation of the extractions in different workings gave the total extraction.

Three classes of workings are considered: (1) rooms and pillars, (2) entries, and (3) pillars outside the panels. These divisions are taken up separately and in order.

In determining the area excavated in the room and pillar area of the panel, that is, the area of the panel mined out with the exception of the room entry, *cdef* and *ghik*, Fig. 1, a calculation of the area of a single room and its cross-cuts was made. This area was multiplied by the number of rooms per panel, proper allowance being made for the fact that there is always one more room than pillars on an entry and that the total area of cross-cuts is calculated from the number of pillars. To calculate the area taken out per room the area lost at the neck was subtracted from the product of the width and the length of the room.

The forms and the dimensions of the room necks and cross-cuts are shown in Fig. 2. The area lost at the room neck in the case of a room 25 feet wide is

$$2 \times 3.5 \times \frac{18 + 12}{2} = 105 \text{ square feet}$$

In all cases it was assumed that cross-cuts were staggered and that the number of cross-cuts through any pillar was either one more or one less than that made through the adjoining pillars. Cross-cuts were so spaced that no working place would be driven more than 60 feet ahead of the air current. This arrangement gives an average of $1\frac{1}{2}$ cross-cuts per pillar for the 200-foot rooms, and $2\frac{1}{2}$ for the 250-foot rooms. This method of arranging cross-cuts is common but not universal. The percentage of area occupied by cross-cuts is small, however, and it makes little difference, so far as the percentage of extraction is concerned, whether the cross-cuts are assumed to be in a straight line or staggered. The area of cross-cuts per pillar in the case of the 250-foot room is

$$2.5 \times 18 \times 25 = 1,125 \text{ square feet}$$

The area of the rooms turned from one entry, with their cross-cuts, assuming 12 rooms per entry and a room length of 250 feet, is

$$12 [(25 \times 250) - 105] + (11 \times 2.5 \times 18 \times 25) = 86,115 \text{ square feet}$$

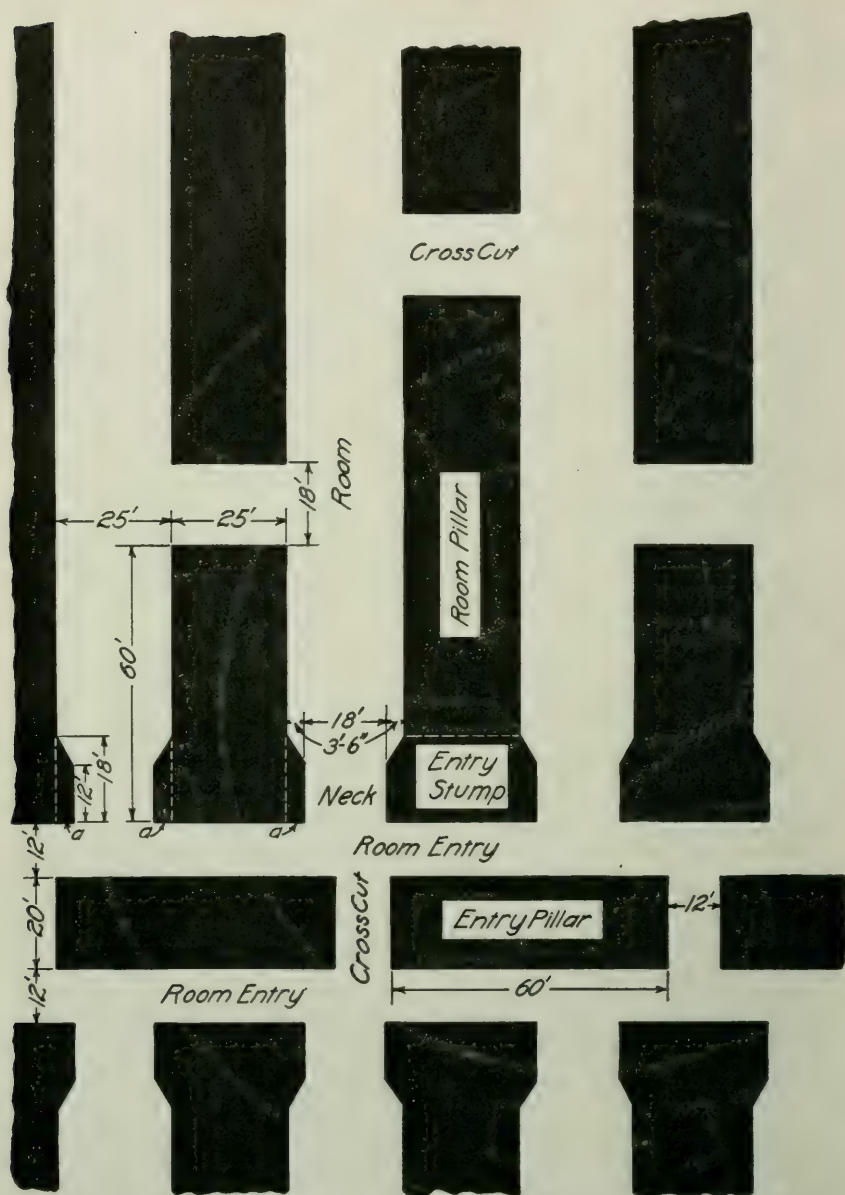


FIG. 2. ROOM ENTRY AND ROOM NECKS

In the following computations it is assumed that rooms are turned from both the room entries, and the area of the number of rooms and room cross-cuts in the panel is

$$2 \times 86,115 = 172,230 \text{ square feet}$$

The area devoted to rooms and pillars in a panel of 12 rooms, 25 feet wide on 50-foot centers and 250 feet long, is

$$[24 \times 25 \times 250] + [22 \times 25 \times 250] = 287,500 \text{ square feet}$$

and the percentage of extraction is

$$\frac{172,230 \times 100}{287,500} = 59.91 \text{ per cent}$$

14. *Lengths of Entries.*—The lengths of entries are obtained by measurement or by calculation. The length given in each case is that of the double entry, e. g., the length of the main entry is 2640 feet.

15. *Percentage of Extraction in Entries.*—With the following notation,

Le = length of entry

We = width of entry

n = number of entries (2 for double entry, 3 for triple entry)

Wp = width of entry pillar

Wc = width of cross-cuts

Cc = cross-cut centers

the percentage of extraction in any entry or group of entries is expressed by the formula:

$$\frac{[(n \times Le \times We) + (n-1) \left(\frac{Le}{Cc} \times Wc \times Wp \right)] \times 100}{(n \times Le \times We) + (n-1) \times Le \times Wp}$$

With the dimensions assumed on page 18, the percentage of extraction in room entries is

$$\frac{[(2 \times 12) + \left(\frac{12}{72} \times 20 \right)] \times 100}{44} = 62.12 \text{ per cent}$$

In the same way the percentage of extraction in main entry and cross entries is

$$\frac{[(2 \times 12) + (\frac{12}{72} \times 25)] \times 100}{49} = 57.48 \text{ per cent}$$

The difference in extraction between the main and cross entries and the room entries is due to the differences in width of entry pillars.

The area extracted in the room entries inside the panel is equal to the area occupied by the entries and entry pillar multiplied by the percentage of extraction:

$$44 \times 575 \times 0.6212 = 15,716 \text{ square feet}$$

16. *Percentage of Extraction Inside the Panel.*—The total area extracted inside the panel is the sum of the areas of rooms with their cross-cuts and of the entries and their cross-cuts.

$$172,230 + 15,716 = 187,946 \text{ square feet}$$

and the percentage of extraction is

$$\frac{187,946 \times 100}{544 \times 575} = 60.09 \text{ per cent}$$

in which 544 is the width of the panel and 575 the length.

17. *Percentage of the Total Area Occupied by Panels.*—In any restricted area, such as that under consideration, there will be in most instances a number of whole panels and parts of others which can be determined by plotting or by computation. In the case under consideration, which is illustrated in Fig. 1, there were 12 whole panels 544 by 575 feet, 3 parts of panels 155 by 575 feet, 1 part 155 by 392 feet, and 4 parts 544 by 392 feet. The total area of the panels was then:

<i>Square Feet</i>
12 × 544 × 575 = 3,753,600
3 × 155 × 575 = 267,375
155 × 392 = 60,760
4 × 544 × 392 = 852,992
4,934,727

The total percentage of area occupied by panels is

$$\frac{4,934,727 \times 100}{6,969,600} = 70.80 \text{ per cent}$$

18. *Percentage of Total Area Extracted in All Panels.*—This is the product of the percentage of total area occupied by panels and the percentage of extraction in panels:

$$70.80 \times 0.6009 = 42.54 \text{ per cent}$$

19. *Entry Area Outside the Panels.*—A double main entry is assumed to be driven across the tract, its area being $2,640 \times 49 = 129,360$ square feet. In the case of the two double cross entries the width is the same, but the length is less by the width of the main entry from which the two cross entries are driven. The area of these two is

$$2 \times 2,591 \times 49 = 253,918 \text{ square feet}$$

The area devoted to the main entry was the same in all instances since only one main entry was assumed. The area of cross entries varied considerably as there were sometimes three cross entries, sometimes two and sometimes only one.

The area of room entries outside the panel is

$$16 \times 44 \times 100 = 70,400 \text{ square feet}$$

In the tract under consideration, illustrated in Fig. 1, there are no fractional widths of cross entry barriers to be considered and all the portions of room entries outside the panels are 100 feet long. In some other cases there were fractions of barrier pillars and therefore different lengths of room entries outside the panels.

The total area occupied by entries outside the panels is the sum of the areas of main entry, cross entries, and room entries with their entry pillars:

	<i>Square Feet</i>
Main entry	129,360
Cross entries	253,918
Room entries	70,400
	453,678

23. *Area Left in Pillars Outside the Panels.*—The only area remaining to be considered is that occupied by barrier pillars and pillars at sides and ends of panels. As it is assumed that this pillar coal is entirely lost the only thing to be considered is the area and the percentage of total area occupied by the pillars. If in any case it is to be assumed that some of this coal is to be saved, the amount thus extracted may be found by multiplying the area of the pillars by the percentage of extraction.

It is, of course, not always true that all the coal thus left is lost, and theoretically this is seldom the case, as it is generally intended that a large part of the coal left, especially in barrier pillars, will be extracted later. In some coal mining districts this coal is extracted, but in the Illinois fields very little of the barrier coal is mined; consequently it seems better to assume complete loss of this coal rather than an arbitrary percentage of recovery.

In the case of each entry barrier the area is the length of the barrier multiplied by its width, minus the area of the entries which extend through it but including the entry pillar. The area of the main entry barrier pillars, as thus defined, is

$$2 \times 100 \times 2640 - [(8 \times 100 \times 12) + (4 \times 25 \times 12)] = 517,200 \text{ square feet}$$

The percentage of the total area devoted to main entry barrier pillars is

$$\frac{517,200 \times 100}{6,969,600} = 7.42 \text{ per cent}$$

This percentage is unusually high because of the small area considered. In the case of a square area of 5,000 acres with one main entry with barrier pillars 100 feet wide, the percentage of area occupied by the main entry barriers is about 1.3 per cent.

The length of the cross entry barrier pillars is the distance across the tract minus the width of the main entry with its two barrier pillars. The area is

$$4 \times 100(2640 - 249) - [(32 \times 100 \times 12) + (16 \times 20 \times 12)] = 914,160 \text{ square feet}$$

The percentage of total area is

$$\frac{914,160 \times 100}{6,969,600} = 13.12 \text{ per cent}$$

The area left in pillars at the ends of panels is, in the cases assumed

$$25 \times (2640 - 249) = 59,775 \text{ square feet}$$

The percentage of the total area occupied by these pillars is

$$\frac{59,775 \times 100}{6,969,600} = 0.86 \text{ per cent}$$

The area of the pillars left at the sides of panels is, in the case assumed .

$$(9 \times 20 \times 575) + (3 \times 20 \times 392) = 127,020 \text{ square feet}$$

The percentage of total area occupied is

$$\frac{127,020 \times 100}{6,969,600} = 1.82 \text{ per cent}$$

The sum of the various items of loss in pillars outside the panels and entries is

Main entry barrier	7.42
Cross entry barrier	13.12
Total in entry barriers	20.54
In pillars at ends of panels	0.86
In pillars at sides of panels	1.82
Total left in pillars outside the panels	23.22

24. *Percentages of Extraction with Different Room Widths.*—

In computing the percentage of total extraction with various other room widths considered: viz., 20, 30, 35, and 40 feet the dimensions of room centers were kept unchanged at 50 feet. It is recognized that this would not be the practice, but a change of room centers would have so complicated the problem as to require a much longer period for the attainment of results. The method of calculation has been clearly indicated and it is possible, by selecting room and pillar widths of the proper ratio in Tables 4, 5, and 6 to obtain close approximations to the percentages of extraction and loss with any widths of room and pillar desired.

It was assumed that the length of the panels and the percentage of total area devoted to panels for each number of rooms per entry

were not changed by these alterations in room and pillar dimensions. This assumption is not strictly true, since the length of the panel varies with the room width; for example, a panel of eight 40-foot rooms to the entry is 390 feet long instead of the 375 feet assumed. The discrepancies are greatest in the instances of widest rooms, because the difference between real panel length and assumed panel length is greatest. There are two errors which partially neutralize each other, and it was found by computation for the extreme cases that the final errors were very small. In the first place if the panel is actually longer than is assumed, the percentage of extraction in the panel is less than that computed. In the second place if the panel is longer than assumed, the total area occupied by panels is greater than that computed. The errors for the first and the last figures in the various columns of Table 4 are as follows: In the column for 20-foot rooms the first figure is 0.05 too high and the last figure is 0.29 too low; in the column for 25-foot rooms the figures are correct; in the column for 30-foot rooms the first figure is 0.05 too low and the last figure 0.04 too high; in the column for 35-foot rooms the first figure is 0.11 too low and the last figure 0.25 too high; in the column for 40-foot rooms the first figure is 0.15 too low and the last figure 0.67 too high. The other figures in each column have errors intermediate between those of the first and last figures. The errors all being less than one per cent, it is apparent that this method of calculation is sufficiently accurate for all purposes for which it is likely to be used, as departures from the projected method of working will account for greater differences between the actual and the computed output than the small errors in the tables.

25. *Tables and Diagrams.*—For convenience in reference the values obtained by the methods described in the preceding pages have been collected in Tables 1-7, which give the percentages of total area occupied by different classes of workings, the percentages of extraction in these different classes, the percentages of total area excavated in the different classes of workings, the percentage of total area won, the lengths of entries and the amounts of narrow work.

Most of the facts given in the tables are shown graphically in Figs. 3 to 9. These figures permit comparison between the results obtained by the use of different dimensions of workings.

For 25-foot rooms, Table 1 shows in column 3 the percentage of

TABLE 1
EXTRACTION IN PANELS

25-FOOT ROOMS

Length of Rooms (Feet)	Number of Rooms per Room Entry	Percentage of Extraction in Room and Pillar Area ¹	Percentage of Extraction inside the Panel	Percentage of Total Area Occupied by Panels	Percentage of Total Area Extracted in Panels
200	8	58.51	58.87	62.17	36.60
	12	57.54	57.99	70.20	40.71
	16	57.06	57.56	77.09	44.37
	20	56.78	57.31	78.45	44.96
	24	56.60	57.15	78.45	44.83
	28	56.47	57.03	79.28	45.21
250	8	60.89	60.92	62.71	38.20
	12	59.91	60.09	70.80	42.54
	16	59.45	59.67	77.76	46.40
	20	59.19	59.43	79.14	47.03
	24	59.01	59.27	79.13	46.90
	28	58.89	59.15	79.97	47.30
300	8	62.39	62.37	63.25	39.45
	12	61.49	61.53	71.41	43.94
	16	61.05	61.12	78.43	47.94
	20	60.80	60.88	79.81	48.59
	24	60.63	60.73	79.81	48.47
	28	60.51	60.62	80.65	48.89

¹Room and pillar area shown by hatching in Fig. 1.

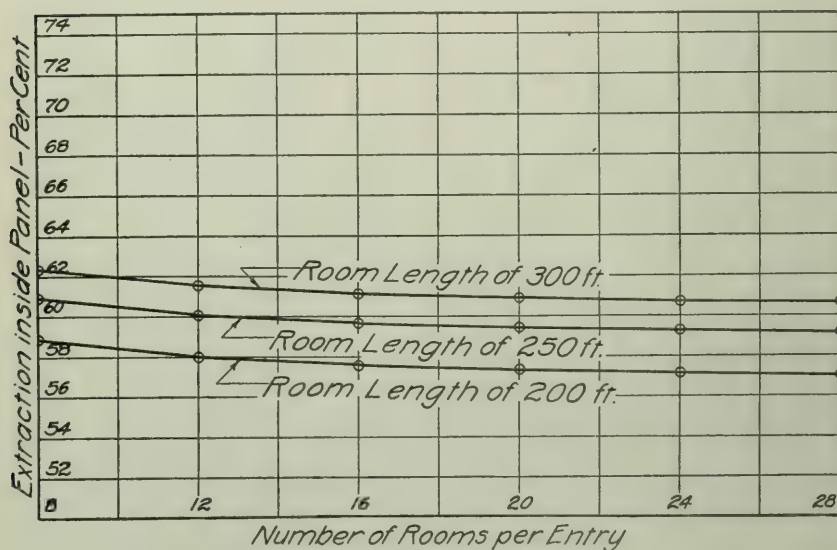


FIG. 3. PERCENTAGE OF EXTRACTION INSIDE THE PANEL FOR ROOMS
250 FEET LONG, 25 FEET WIDE, ON 50-FOOT CENTERS

extraction in the room and pillar area obtained with each length of room and each number of rooms per entry; in column 4 the total percentage of extraction inside the panel, that is, the sum of the extraction in rooms and room cross-cuts, and in room entries; in column 5 the percentage of the total area included in panels; and in column 6 the percentage of the total area extracted in panels. The percentage extracted in the panels plus the percentage extracted in the entries outside the panels gives the total percentage of extraction.

The values in column 4 of Table 1, the percentage of extraction inside the panel for rooms 25 feet wide, are illustrated by Fig. 3. For a given width of room and pillar the percentage of extraction inside the panel decreases somewhat as the number of rooms per entry increases, because the proportion of the total panel area remaining in pillars increases as the number of rooms increases and the percentage of extraction correspondingly decreases. With only two rooms and one pillar approximately $\frac{1}{3}$ of the coal is left in the pillar, while with the 10 rooms and 9 pillars $\frac{1}{9}$ remain and with 20 rooms and 19 pillars $\frac{1}{9}$ remain.

The values in column 5 of Table 1 are illustrated in Fig. 4 which shows the percentage of total area included in panels for 25-foot rooms, 200 feet, 250 feet, and 300 feet long respectively, and for 8, 12, 16, 20, 24, and 28 rooms per entry. These diagrams show that the percentage of area devoted to panels increases with the length of the room and the number of rooms per entry. The increase is especially rapid for the smaller number of rooms per entry and comparatively small for the larger number of rooms per entry.

It will be noticed that there is a reversal in the direction of the lines at 24 rooms per entry shown in the broken lines based on the figures in the table, and that there is no corresponding change in direction of the diagrams for percentage of extraction inside the panel. These facts show that the drop in the diagrams of total extraction (Fig. 6) at 24 rooms per entry is due to the irregularity of the increase of percentage of total area included in panels, which in turn is due to the limited area considered. The solid lines (Figs. 4 and 6) show the positions when a large area is considered, and the same results are reached by calculation for 25 rooms per entry.

It will also be noticed that there is a comparatively rapid change in the direction of the lines when there are about 16 rooms per panel. This fact indicates that with 16 rooms per panel, or less, the percent-

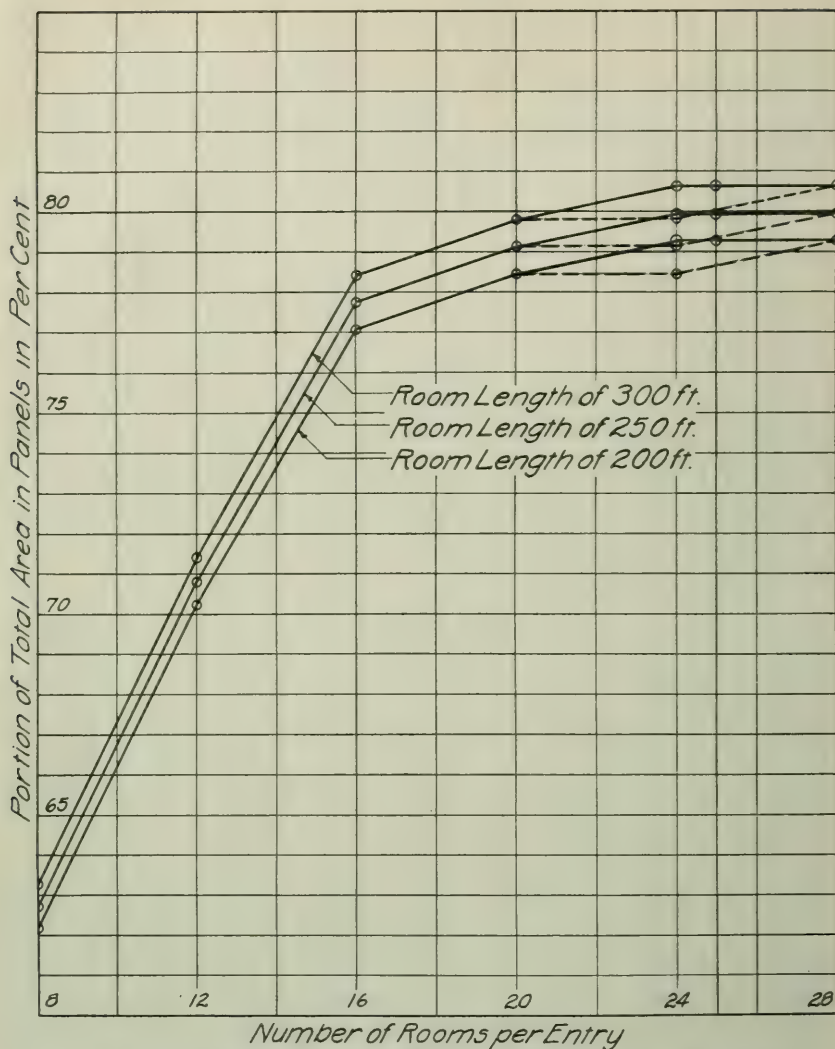


FIG. 4. PERCENTAGE OF TOTAL AREA INCLUDED IN PANELS FOR ROOMS 25 FEET WIDE, ON 50-FOOT CENTERS

age of area occupied by panels increases rapidly with the number of rooms per entry. For 16 rooms, or more, the increase is slow. This change also shows as does the diagram for total percentage of extraction, that this percentage increases comparatively rapidly with the

increase of number of rooms per entry to about 16 and that after this number is reached the rate of increase is small.

TABLE 2
EXTRACTION IN ENTRIES

Length of Rooms (Feet)	Number of Rooms per Room Entry	Percentage of Total Area Occupied by Entries					Percentage of Total Area Extracted in Entries			
		Main Entry	Cross Entry	Room Entry		Total	Main Entry	Cross Entry	Room Entry	Total
				Outside Panel	Inside Panel					
200	8	1.86	5.46	1.79	5.92	15.03	1.07	3.14	4.79	9.00
	12	1.86	3.64	1.26	6.68	13.44	1.07	2.09	4.93	8.09
	16	1.86	1.82	0.76	7.34	11.78	1.07	1.05	5.03	7.15
	20	1.86	1.82	0.63	7.47	11.78	1.07	1.05	5.03	7.15
	24	1.86	1.82	0.63	7.47	11.78	1.07	1.05	5.03	7.15
	28	1.86	1.82	0.63	7.55	11.86	1.07	1.05	5.08	7.20
250	8	1.86	5.46	1.43	4.74	13.49	1.07	3.14	3.83	8.04
	12	1.86	3.64	1.01	5.35	11.86	1.07	2.09	3.95	7.11
	16	1.86	1.82	0.61	5.87	10.16	1.07	1.05	4.02	6.14
	20	1.86	1.82	0.51	5.97	10.16	1.07	1.05	4.03	6.15
	24	1.86	1.82	0.51	5.97	10.16	1.07	1.05	4.03	6.15
	28	1.86	1.82	0.51	6.04	10.23	1.07	1.05	4.07	6.19
300	8	1.86	5.46	1.43	4.74	13.49	1.07	3.14	3.83	8.04
	12	1.86	3.64	1.01	5.35	11.86	1.07	2.09	3.95	7.11
	16	1.86	1.82	0.61	5.87	10.16	1.07	1.05	4.02	6.14
	20	1.86	1.82	0.51	5.97	10.16	1.07	1.05	4.03	6.15
	24	1.86	1.82	0.51	5.97	10.16	1.07	1.05	4.03	6.15
	28	1.86	1.82	0.51	6.04	10.23	1.07	1.05	4.07	6.19

Table 2 gives the percentage of total area occupied by entries and the percentage of total area extracted in entries, all for rooms 25 feet wide. Column 3 gives the percentage of total area in the main entry, column 4 the percentage of total area in the cross entries, column 5 the percentage of total area in the room entries outside the panel, column 6 the percentage of total area in the room entries inside the panel, and column 7 the total percentage of area occupied by entries. Column 8 gives the percentage of total area extracted in main entry, column 9 the percentage extracted in cross entries, column 10 the percentage extracted in room entries, and column 11 the total percentage of area extracted in entries.

The values in Table 2 are illustrated by Fig. 5 which shows the percentage of total area occupied by entries, including the entry pillars, for different numbers of rooms per entry and different lengths of rooms. The diagrams are drawn for 25-foot rooms, but, as shown in the discussion of the methods of calculation, they would be only slightly changed if different room widths were considered.

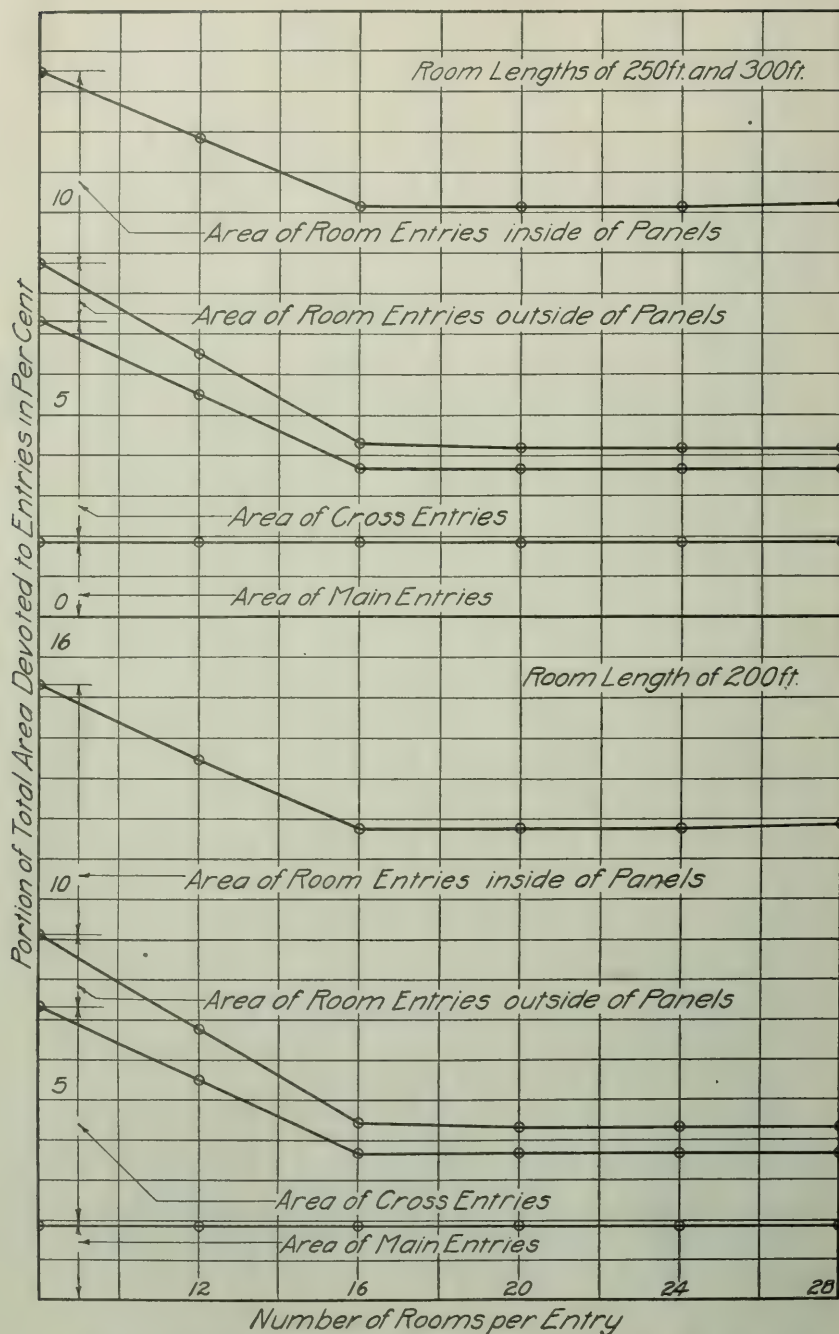


FIG. 5. PERCENTAGE OF TOTAL AREA OCCUPIED BY ENTRIES FOR ROOMS 25 FEET WIDE, ON 50-FOOT CENTERS

Column 3 of Table 3 shows the amounts of narrow work in entries. Columns 4, 5, 6, and 7 give respectively the length of main

TABLE 3
LENGTH OF ENTRIES AND YARDS OF NARROW WORK

Length of Rooms (Feet)	Number of Rooms per Room Entry	Yards of Narrow Work	Length of Double Entries in Feet ¹			
			Main Entry	Cross Entry	Room Entry	Total
200	8	17192	2640	7773	12215	22628
	12	15488	2640	5182	12585	20407
	16	13707	2640	2591	12830	18061
	20	13707	2640	2591	12830	18061
	24	13707	2640	2591	12830	18061
	28	13804	2640	2591	12955	18186
250	8	15333	2640	7773	9772	20185
	12	13591	2640	5182	10068	17889
	16	11752	2640	2591	10264	15495
	20	11771	2640	2591	10264	15495
	24	11771	2640	2591	10264	15495
	28	11848	2640	2591	10364	15595
300	8	15333	2640	7773	9772	20185
	12	13591	2640	5182	10068	17889
	16	11752	2640	2591	10264	15495
	20	11771	2640	2591	10264	15495
	24	11771	2640	2591	10264	15495
	28	11848	2640	2591	10364	15595

¹These lengths refer to pairs of entries, not to single entries; i. e., they represent haulage distances along the entries. The total length of narrow work for which yardage is paid is therefore double the length given, plus the sum of the lengths of cross-cuts.

entries, cross entries, room entries and total entries, in all cases without entry cross-cuts. It should be noted that these are the lengths of double entries and not of single entries; for example, the length of the main entry, 2640 feet, is the distance across the tract.

The total cross entry length does not vary with the length of rooms, but decreases with the increase in the number of rooms per entry. This decrease is actually more regular than is indicated, because the table is for a small tract in which a cross entry is occasionally forced outside the boundary by increase of number of rooms per entry.

In the tract considered the total room entry length is the same for 250-foot and 300-foot rooms, but is greater for 200-foot rooms. If a large area were considered, the lengths for the 250-foot and 300-foot rooms would not coincide, but the length for the 250-foot rooms would lie between those of the 200-foot and 300-foot rooms. The total length of room entries increases slightly as the number of rooms per entry increases.

TABLE 4
PERCENTAGE OF EXTRACTION IN PANELS, IN ENTRIES, AND TOTAL EXTRACTION¹

Length of Rooms (Feet)	Number of Rooms per Room Entry	Percentage of Extraction Inside Each Panel					Percentage of Total Area Extracted in All Panels					Percentage of Total Area Extracted in Entries Outside Panels	Total Percentage Extracted				
		20-ft. Rooms	25-ft. Rooms	30-ft. Rooms	35-ft. Rooms	40-ft. Rooms	20-ft. Rooms	25-ft. Rooms	30-ft. Rooms	35-ft. Rooms	40-ft. Rooms		20-ft. Rooms	25-ft. Rooms	30-ft. Rooms	35-ft. Rooms	40-ft. Rooms
200	8	51.12	58.87	66.62	74.38	82.13	31.78	36.60	41.42	46.24	51.06	5.32	37.10	41.92	46.74	51.56	56.38
	12	50.46	57.99	65.52	73.05	80.59	35.42	40.71	46.00	51.28	56.57	3.94	39.36	44.65	49.94	55.22	60.51
	16	50.14	57.56	64.99	72.41	79.84	38.65	44.37	50.10	55.82	61.55	2.59	41.24	46.96	52.69	58.41	64.14
	20	49.95	57.31	64.67	72.04	79.40	39.19	44.96	50.73	56.51	62.29	2.51	41.70	47.47	53.24	59.02	64.80
	24	49.82	57.15	64.47	71.79	79.10	39.08	44.83	50.58	56.32	62.05	2.51	41.59	47.34	53.09	58.83	64.56
	28	49.74	57.03	64.32	71.61	78.91	39.43	45.21	50.99	56.77	62.56		41.94	47.72	53.50	59.28	65.07
250	8	53.25	60.92	68.59	76.26	83.93	33.39	38.20	43.01	47.82	52.63	5.10	38.69	43.30	48.11	52.92	57.73
	12	52.65	60.09	67.52	74.92	82.39	37.27	42.54	47.80	53.04	58.33	3.79	41.06	46.33	51.59	56.83	62.12
	16	52.35	59.67	66.99	74.01	81.62	40.70	46.40	52.09	57.55	63.47	2.50	43.20	48.90	54.59	60.15	65.97
	20	52.18	59.43	66.67	73.93	81.17	41.30	47.03	52.76	58.51	64.24	2.44	43.74	49.47	55.20	60.95	66.68
	24	52.05	59.27	66.46	73.67	80.86	41.19	46.90	52.60	58.30	63.98	2.44	43.63	49.34	55.04	60.74	66.42
	28	51.98	59.15	66.36	73.50	80.67	41.57	47.30	53.07	58.78	64.51	2.44	44.01	49.74	55.51	61.22	66.95
300	8	54.75	62.37	69.98	77.60	85.21	34.62	39.45	44.26	49.08	53.90	5.08	39.70	44.53	49.34	54.16	58.98
	12	54.17	61.53	68.89	76.26	83.62	38.68	43.94	49.19	54.46	59.71	3.79	42.47	47.73	52.98	58.25	63.50
	16	53.88	61.12	68.37	75.61	82.85	42.26	47.94	53.63	59.30	64.98	2.50	44.76	50.44	56.13	61.80	67.48
	20	53.71	60.88	68.06	75.23	82.40	42.57	48.59	54.32	60.04	65.76	2.44	45.31	51.03	56.76	62.48	68.20
	24	53.60	60.73	67.85	74.98	82.10	42.78	48.47	54.15	59.84	65.52	2.44	45.22	50.91	56.59	62.28	67.96
	28	53.52	60.62	67.71	74.80	81.89	43.16	48.89	54.61	60.33	66.04	2.44	45.60	51.33	57.05	62.77	68.48

¹Room centers 50 feet in all cases.

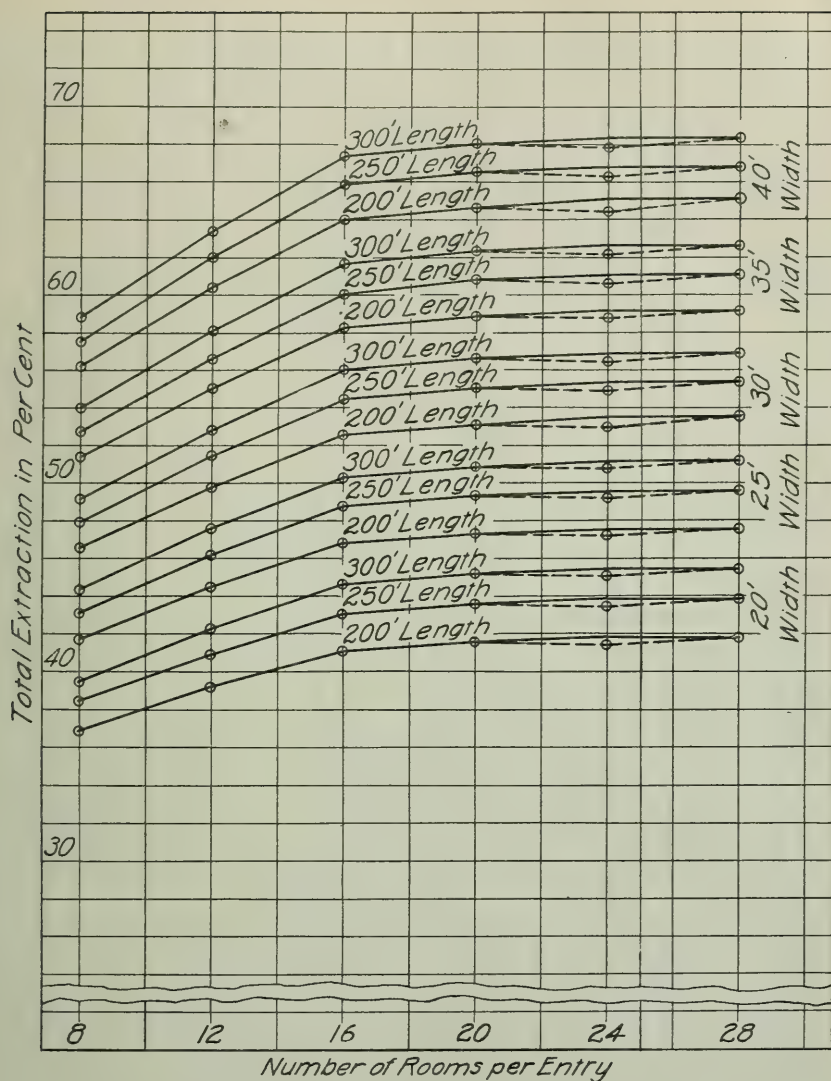


FIG. 6. TOTAL PERCENTAGE OF EXTRACTION

The decrease in length of cross entries with increase of number of rooms per entry ceases at about 16 rooms per entry. If a larger area were considered, the change would be less abrupt than it is.

Table 4 gives the percentages of extraction for all widths of rooms considered. The first group of figures in columns 3, 4, 5, 6, and 7, gives the percentage of extraction inside the panel for each width of room, for each length of room and for each number of rooms per entry. The second group of figures, given in columns 8, 9, 10, 11, and 12, gives the percentage of total area extracted in panels for each width of room, each length of room, and each number of rooms per entry. In each case this percentage is obtained by multiplying the percentage of extraction inside the panel by the percentage of area occupied by panels. The values in column 13 give the percentage of area extracted in entries outside the panels.

The third group of figures, given in columns 14, 15, 16, 17, and 18, gives the total percentage of extraction. This percentage is obtained in each case by adding to the percentage of area extracted in panels the percentage of area extracted in entries outside the panels.

It will be noted that the total percentage of extraction is increased by increasing the length of rooms, the width of the rooms and the number of rooms per entry.

The values for total extraction given in Table 4 are shown graphically by Fig. 6. This set of diagrams shows plainly, in the broken lines plotted from the figures in the table, one of the irregularities resulting from the use of a small area as a basis for calculation: that is, the apparent drop in total percentage of extraction at 24 rooms per entry. The percentage of extraction does not actually drop at this point, however, the apparent drop being due to the consideration of a limited area. Calculations for 25 rooms per entry place the curve at its approximately proper position, and the solid lines show this position.

Table 5 shows the percentage of loss inside the panel and the percentage of total area lost inside the panels, for all conditions considered. Columns 3 to 7 inclusive give the percentages of loss inside the panel for the different conditions; columns 8 to 12 inclusive give the percentage of total area lost inside the panels. These latter figures are obtained by multiplying the percentage of area devoted to panels by the percentage of loss inside the panels, which is obtained by subtracting the percentage of extraction inside the panel from one hundred.

Table 6 gives the percentages of total area left in pillars outside panels; that is, all coal left in the mine except that in room pillars

TABLE 5
PERCENTAGE LOST IN PANELS

Length of Rooms (Feet)	Number of Rooms per Room Entry	Percentage of Loss Inside Panels.					Percentage of Total Area Lost Inside Panels				
		20-ft. Rooms	25-ft. Rooms	30-ft. Rooms	35-ft. Rooms	40-ft. Rooms	20-ft. Rooms	25-ft. Rooms	30-ft. Rooms	35-ft. Rooms	40-ft. Rooms
200	8	48.88	41.13	33.38	25.62	17.87	30.39	25.57	20.75	15.93	11.11
	12	49.54	42.01	34.48	26.95	19.41	34.64	29.49	24.20	18.92	13.63
	16	49.86	42.44	35.01	27.59	20.16	38.44	32.72	26.99	21.27	15.54
	20	50.05	42.69	35.33	27.96	20.60	39.26	33.49	27.72	21.93	16.16
	24	50.18	42.85	35.53	28.21	20.90	39.37	33.62	27.87	22.13	16.40
	28	50.26	42.97	36.17	28.39	21.67	39.85	33.99	28.68	22.51	17.18
250	8	46.75	39.08	31.41	23.74	16.07	29.32	24.51	19.70	14.89	10.08
	12	47.35	39.91	32.48	25.08	17.61	33.52	28.26	23.00	17.76	12.47
	16	47.65	40.33	33.01	25.99	18.38	37.05	31.36	25.67	20.21	14.29
	20	47.82	40.57	33.33	26.07	18.73	37.84	32.11	26.38	20.63	14.82
	24	47.96	40.73	33.53	26.33	19.14	37.94	32.23	26.53	20.83	15.15
	28	48.02	40.85	33.64	26.50	19.33	38.40	32.67	26.90	21.19	15.46
300	8	45.25	37.63	30.02	22.40	14.79	28.62	23.80	18.99	14.17	9.35
	12	45.83	38.47	31.11	23.74	16.38	32.73	27.47	22.22	16.95	11.70
	16	46.12	38.88	31.63	24.39	17.15	36.17	30.49	24.81	19.13	13.45
	20	46.29	39.12	31.94	24.77	17.60	36.94	31.22	25.49	19.77	14.05
	24	46.40	39.27	32.15	25.02	17.90	37.03	31.34	25.66	19.97	14.29
	28	46.48	39.38	32.29	25.20	18.11	37.49	31.76	26.04	20.33	14.61

TABLE 6

PERCENTAGE LOST IN PILLARS OUTSIDE THE PANELS EXCEPT IN ENTRIES

Length of Rooms (Feet)	Number of Rooms per Room Entry	Percentage of Total Area Left in Pillars Outside Panel Except Entry Pillars					
		Main Entry Barriers	Cross Entry Barriers	Total in Entry Barriers	At Ends of Panels	At Sides of Panels	Total
200	8	7.34	18.41	25.75	1.72	2.15	29.62
	12	7.42	12.96	20.38	0.86	2.43	23.67
	16	7.50	7.82	15.32	0.86	2.67	18.85
	20	7.50	6.48	13.98	0.86	2.72	17.56
	24	7.50	6.48	13.98	0.86	2.72	17.56
	28	7.50	6.48	13.98	0.00	2.74	16.72
250	8	7.34	18.63	25.97	1.72	1.61	29.30
	12	7.42	13.12	20.54	0.86	1.82	23.22
	16	7.50	7.92	15.42	0.86	2.00	18.28
	20	7.50	6.56	14.06	0.86	2.04	16.96
	24	7.50	6.56	14.06	0.86	2.04	16.96
	28	7.50	6.56	14.06	0.00	2.06	16.12
300	8	7.34	18.63	25.97	1.72	1.08	28.77
	12	7.42	13.12	20.54	0.86	1.22	22.62
	16	7.50	7.92	15.42	0.86	1.34	17.62
	20	7.50	6.56	14.06	0.86	1.36	16.28
	24	7.50	6.56	14.06	0.86	1.36	16.28
	28	7.50	6.56	14.06	0.00	1.37	15.43

and entry pillars. Column 3 gives the percentage of total area occupied by the main entry barriers; column 4 the percentage of total area occupied by cross entry barriers; and column 5 the percentage of total area in all entry barriers, the sum of the two preceding columns. Column 6 gives the percentage of total area left in pillars at ends of panels, column 7 the percentage of total area left in pillars at sides of panels, and column 8 the percentage of total area left in pillars outside the panels except in entries. Column 8 represents the sum obtained by adding together the proper figures in columns 3, 4, 6, and 7.

TABLE 7
EXTRACTION IN WIDE WORK AND IN NARROW WORK

Length of Rooms (Feet)	Number of Rooms per Room Entry	Percentage of Total Extraction Obtained from Narrow Work					Percentage of Total Extraction Obtained from Wide Work				
		20-ft. Rooms	25-ft. Rooms	30-ft. Rooms	35-ft. Rooms	40-ft. Rooms	20-ft. Rooms	25-ft. Rooms	30-ft. Rooms	35-ft. Rooms	40-ft. Rooms
200	8	24.26	21.47	19.26	17.46	15.96	75.74	78.53	80.74	82.54	84.04
	12	20.55	18.12	16.20	14.65	13.37	79.45	81.88	83.80	85.35	86.63
	16	17.34	15.23	13.57	12.24	11.15	82.66	84.77	86.43	87.76	88.85
	20	17.15	15.06	13.43	12.11	11.03	82.85	84.94	86.57	87.89	88.97
	24	17.19	15.10	13.47	12.15	11.07	82.81	84.90	86.53	87.85	88.93
	28	17.17	15.09	13.46	12.15	11.07	82.83	84.91	86.54	87.85	88.93
250	8	20.78	18.57	16.71	15.19	13.93	79.22	81.43	83.29	84.81	86.07
	12	17.32	15.35	13.78	12.51	11.45	82.68	84.65	86.22	87.49	88.55
	16	14.21	12.56	11.19	10.21	9.31	85.79	87.44	88.81	89.79	90.69
	20	14.06	12.43	11.14	10.09	9.22	85.94	87.57	88.86	89.91	90.78
	24	14.10	12.47	11.17	10.13	9.26	85.90	87.53	88.83	89.87	90.74
	28	14.07	12.45	11.15	10.11	9.25	85.93	87.55	88.85	89.89	90.75
300	8	20.25	18.06	16.30	14.85	13.63	79.75	81.94	83.70	85.15	86.37
	12	16.74	14.90	13.42	12.21	11.20	83.26	85.10	86.58	87.79	88.80
	16	13.72	12.17	10.94	9.94	9.10	86.28	87.83	89.06	90.06	90.90
	20	13.57	12.05	10.84	9.84	9.02	86.43	87.95	89.16	90.16	90.98
	24	13.60	12.08	10.87	9.87	9.05	86.40	87.92	89.13	90.13	90.95
	28	13.57	12.06	10.85	9.86	9.04	86.43	87.94	89.15	90.14	90.96

Table 7 gives a comparison between the total extraction made in narrow work and that made in wide work. Columns 3 to 7, inclusive, give the percentage of total extraction obtained from narrow work; that is, from entries and entry cross-cuts for all conditions considered. In each case the total extraction, whatever the actual figure, is considered 100 per cent. Columns 8 to 12, inclusive, give the percentage of total extraction obtained from wide work; that is, from rooms, room necks, and room cross-cuts. When these values are considered, it should be remembered that the limit between wide work and narrow work has been set arbitrarily. It is considered for

the purpose of these calculations that all workings less than 18 feet in width are narrow work and all workings 18 feet or more in width are wide work. It is to be noted that the percentage of the total extraction obtained from narrow work decreases as the length of rooms increases, as the number of rooms per entry increases, and as the width of rooms in relation to width of room pillars increases.

As narrow work is more expensive than wide work, efforts will be made to reduce it to the minimum in places where the conditions of roof and floor permit. This reduction can sometimes be accomplished by increasing the width of entries and entry cross-cuts. Where this increase is impossible, the only means of reducing the amount of narrow work is by decreasing the length of entries, assuming that room cross-cuts and room necks are wide work. This assumption, however, is not always true. The work of J. C. Quade (see Appendix I) illustrates the reduction of narrow work by increase of the width of room cross-cuts.

Summaries of the percentages won and lost in different portions of the workings are given in Figs. 7, 8, and 9, which illustrate the results with rooms 25 feet wide, and 200, 250, and 300 feet long respectively. In each case the total height of the diagram represents 100 per cent of area. The height from the bottom border to the first line represents the percentage of total area extracted inside the panels; the height from the first line to the second represents the percentage extracted in entries outside the panels; the height from the second line to the third represents the percentage lost in entries outside the panels; the height from the third line to the fourth represents the percentage lost in pillars outside the panels; and the height from the fourth line to the top of the figure represents the percentage lost inside the panels. As these diagrams are based only upon results with 25-foot rooms on 50-foot centers, no changes of percentage of extraction are involved that are dependent upon change of room width.

These diagrams illustrate the final disposal of the coal in the area considered; they show the amounts won and lost, and the general distribution of extraction and losses. The coal extracted comes from panels and from entries outside the panels, the larger part coming from the panels. As the number of rooms per entry increases, the amount of coal taken from the panels increases, but in the example considered it remains fairly constant after the number of rooms per entry reaches about twenty.

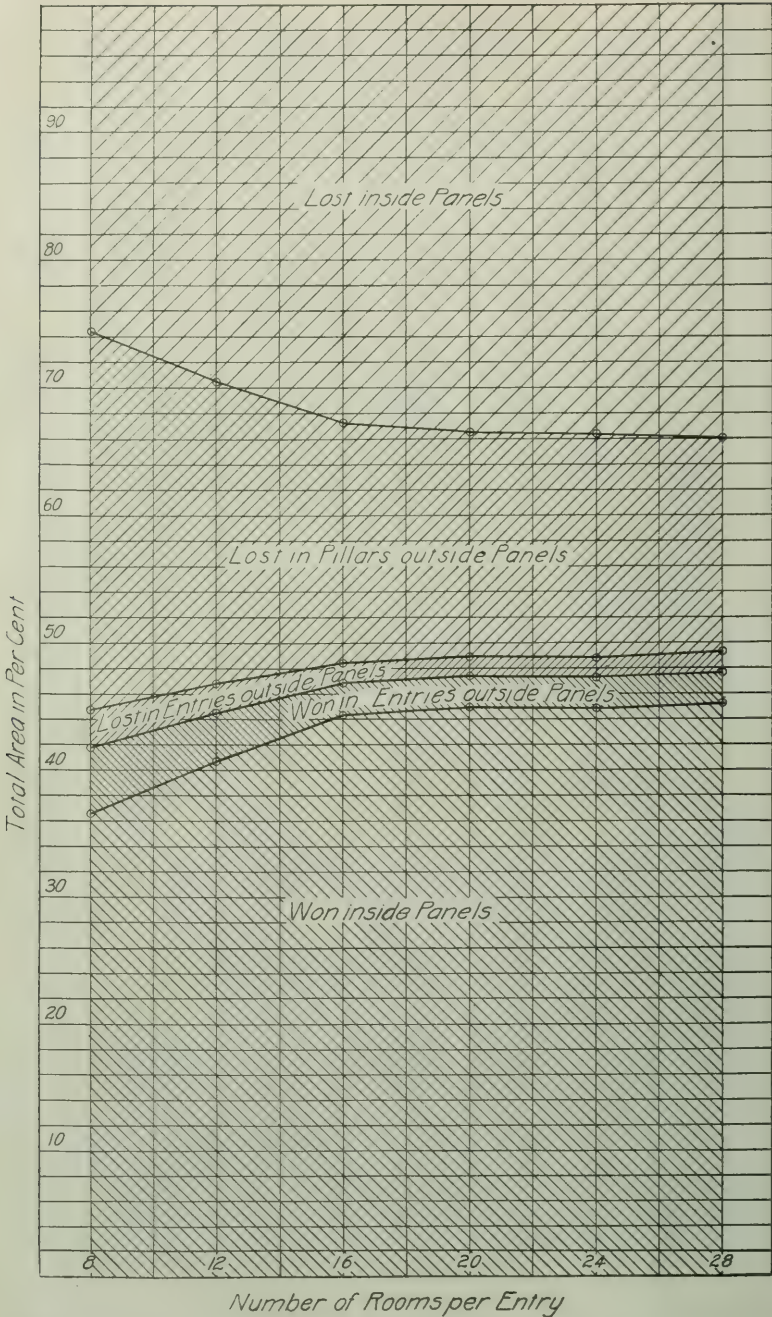


FIG 7 DISTRIBUTION OF EXTRACTION AND LOSS FOR ROOMS 200 FEET LONG, 25 FEET WIDE, ON 50-FOOT CENTERS

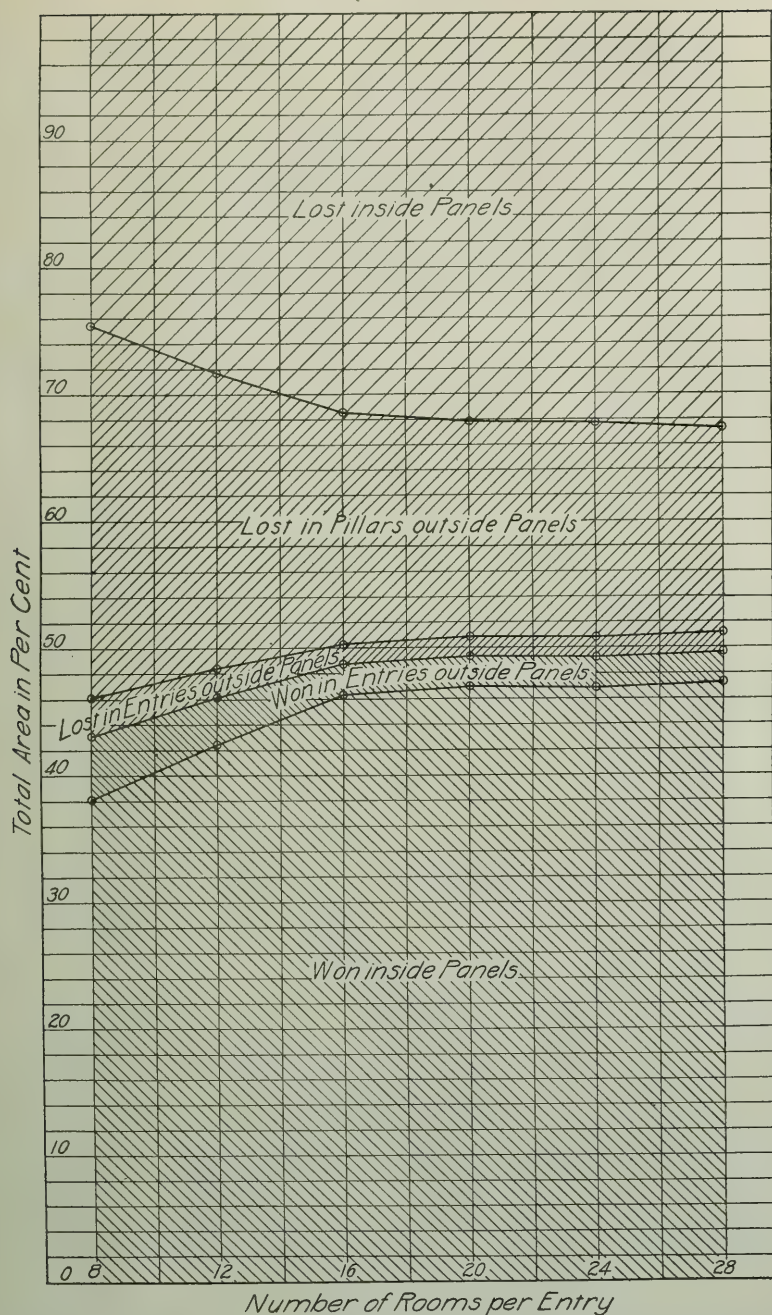


FIG. 8. DISTRIBUTION OF EXTRACTION AND LOSS FOR ROOMS 250 FEET LONG, 25 FEET WIDE, ON 50-FOOT CENTERS

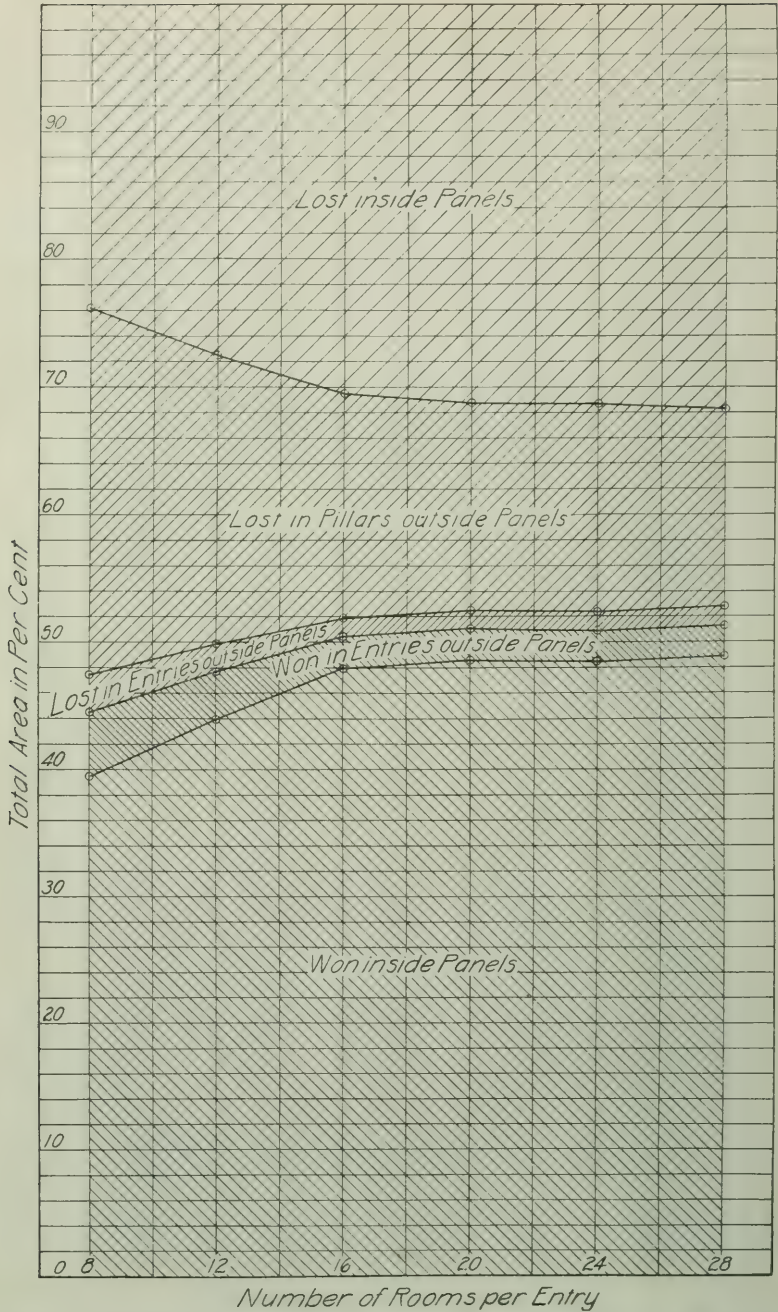


FIG. 9. DISTRIBUTION OF EXTRACTION AND LOSS FOR ROOMS 300 FEET LONG, 25 FEET WIDE, ON 50-FOOT CENTERS

With the increase of number of rooms per entry there is a slight decrease in the percentage extracted from entries outside the panels and also a slight decrease in the coal lost in entries outside the panels, both decreases being due to reduction of area occupied by entries. It is shown plainly that the amount of coal lost and won in entries is not large in any case.

One thing clearly indicated is that the increased extraction which accompanies increase of number of rooms per entry is due largely to a decrease in loss in pillars outside the panels; that is, to decrease of space occupied by barrier pillars. It is also shown that this decrease is much less rapid after rather than before approximately 16 rooms per entry have been reached and that beyond 20 rooms per entry there is very little change.

The fact that the lines become nearly horizontal after 16 to 20 rooms per entry have been reached shows that no material increase of percentage of extraction can be made by further increasing the number of rooms per entry. Comparison of the three diagrams shows also that very slight additional extraction can be accomplished by lengthening rooms. It follows, therefore, that the only two ways of increasing extraction are by increase of ratio of room width to pillar width and by extraction of pillar coal. These two methods may be said to reduce the loss in room pillars, but by entirely different means. It has been proved by experience that attempts to increase room width at the expense of pillar width are dangerous, and it is believed that the greatest ratio of room width used in the preceding discussion,—namely, four to one, considerably exceeds any limit which would ordinarily be safe for operation. It therefore follows that increase of extraction can be attained only by adopting some method for removing pillar coal after the rooms have been driven.

26. *Other Methods of Computation.*—It is recognized that the inclusion of the main entry and its barrier pillars in the tract considered gives percentages of extraction that must be changed somewhat if applied to larger areas, because the ratio of barrier pillar to total area is greater than would be the case in a larger area. This error could be avoided to some extent by choosing the part of the mine to be examined so that the main entry would not be included; thus the computed extraction would be a little too high.

Irregularities due to the limiting of the area considered could be

avoided by a method of computation suggested by C. W. Hippard. Instead of a unit area of 160 acres, the area served by a pair of room entries with half of the adjoining cross entry and barriers and half of the surrounding fire pillars is considered. Such an area, which may be called a unit panel, is shown enclosed by dotted lines in Fig. 10.

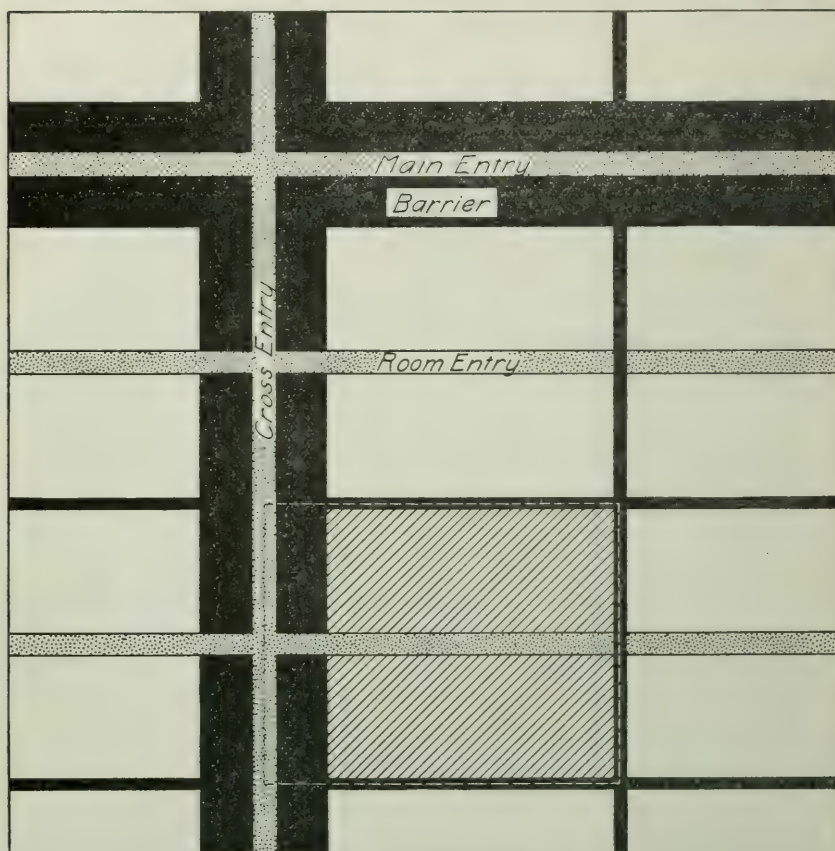


FIG. 10. UNIT PANEL

A single panel with its proper share of cross entry, barriers, and fire pillars is considered a true sample of the mine. The area of the tract considered is not constant, but changes with length of rooms, width of rooms, and number of rooms per panel. As the proportion of the main entry and barriers properly chargeable to this unit area changes with the size of the tract considered, it is best not to include

main entry and barriers in the calculation. Calculated percentages of extraction are then a little too high.

The following computation by this method illustrates the procedure. The dimensions considered are those given on page 18.

Area of panel except room entry, (p. 21),	287,500 square feet
Percentage of extraction in room-and-pillar area, (p. 21),	59.91 per cent
Area excavated in panel except room entry,	
$0.5991 \times 287,500 =$	172,241 square feet
Area occupied by room entry,	
$44 \times 675 =$	29,700 square feet
Percentage of extraction in room entry,	
(p. 21),	62.12 per cent
Area excavated in room entry,	
$0.6212 \times 29,700 =$	18,450 square feet
Area occupied by cross entry,	
$\frac{1}{2} \times 49 \times 564 =$	13,818 square feet
Percentage of extraction in cross entry,	
(p. 22),	57.48 per cent
Area excavated in cross entry,	
$0.5748 \times 13,818 =$	7,943 square feet
Total area excavated	198,634 square feet
Area of tract considered,	
$564 \times 712 =$	401,568 square feet
Percentage of extraction	
$\frac{198,634 \times 100}{401,568} =$	49.47 per cent

This result is 3.14 per cent greater than the extraction calculated by the method described on pages 18 to 24, the difference being due to the exclusion of the main entry and its barriers in the unit panel method. Calculations by the latter method with other numbers of rooms per entry give the following results:

	<i>Extraction</i>
16 rooms per entry	50.98 per cent
20 rooms per entry	51.96 per cent
24 rooms per entry	52.64 per cent
28 rooms per entry	53.14 per cent

The percentages thus obtained agree closely with those previously calculated.

APPENDIX I

COST OF PRODUCTION AND THE PERCENTAGE OF EXTRACTION
IN FULTON COUNTY

WORK OF J. C. QUADE

An investigation of the percentage of extraction in the Fulton County field has been made by J. C. Quade, Chief Engineer of the Big Creek Coal Company and of the Saline County Coal Company. The results of this investigation are in part reproduced in the following pages through the courtesy of Mr. Quade who has reviewed the summary.

These computations were made chiefly to find means of reducing the cost of production, the computation of extraction being incidental but necessary to the computation of cost. The results show that the highest percentage of extraction accompanied the lowest cost of production per thousand tons.

In making computations of cost no attention was paid to the total cost of production, but only to the items which would be directly modified by changes of dimensions of workings. The values of these were determined in part by the prices fixed in the agreement with the United Mine Workers and in part by practice in the Fulton County field.

The items considered in the computation are:

Yardage paid for narrow work.

Room turning.

Switch laying.

Wood track.

Props.

These items are intended to cover labor and materials not directly employed in the extraction of coal. The materials considered are those from which little if any salvage is expected. Such large items of expense as mining, haulage, ventilation, drainage, interest on capital and amortization are omitted because they are little affected by the changes contemplated. The expense of maintaining the various items considered is small in comparison with the total cost of production,

but the calculation includes those items which are most immediately and completely affected by changes in the dimensions of workings.

The method of computation was determined by the fact that the company had an area of 160 acres in Fulton County which was soon to be developed. The tract was in the form of a square with public roads on two sides, coal owned by the company on the third side, and coal not owned by the company on the fourth side. It was therefore necessary to leave pillars along three borders but not along the fourth. This tract was laid out with two main entries, and with six cross entries where 210-foot rooms are considered and seven cross entries where 180-foot rooms are considered as shown in Fig. 11. The form of the field and the necessity of leaving boundary pillars in-

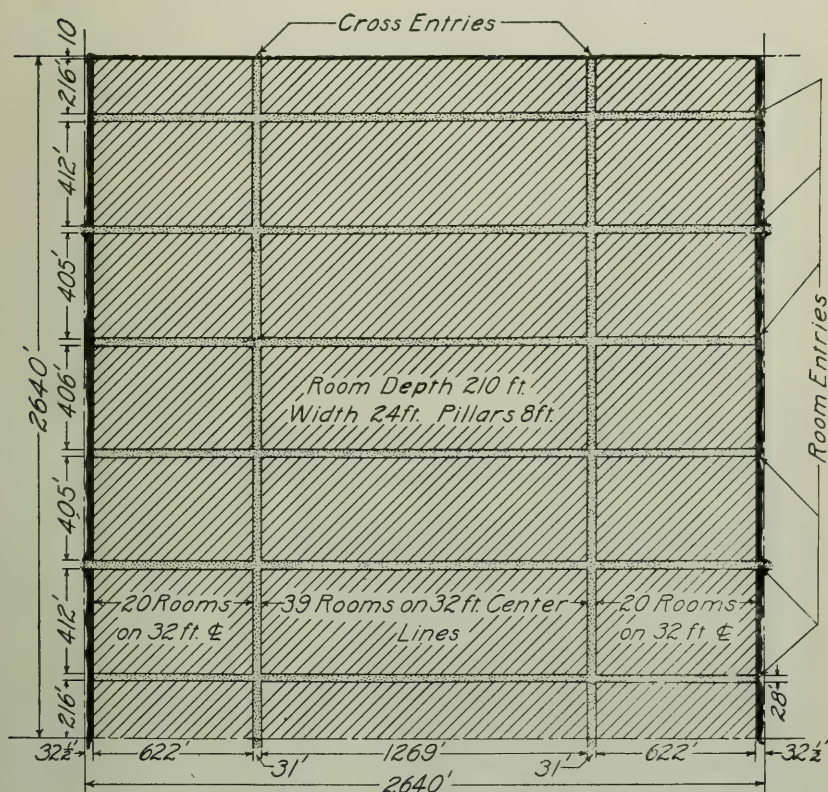


FIG. 11. MAP OF 160 ACRES FOR J. C. QUADE'S COMPUTATION

fluenced both the lengths of entries and the number of rooms. The coal lying east and west of this tract was developed later; hence two pairs of room entries were extended through the boundary pillars on each side to become the cross entries of the newer developments.

Only two lengths of rooms were considered: 180 feet because that length was then being used by the company, and 210 feet because experience had shown this to be the maximum length for a room which could commonly be kept open for the time required to complete extraction without considerable expense for retimbering.

An analysis of the fixed costs in the district in which the mine is located showed that the yardage paid for narrow work in room cross-cuts was responsible for a considerable share of these costs. This yardage could be eliminated by driving room cross-cuts wider than the limit for which yardage is paid, or could be reduced by decreasing the length of the room cross-cuts by making pillars narrower. The calculations involve both methods.

The following items of cost are based upon conditions in the Fulton County field at the time when the calculations were made.

Mining rates fixed by agreement between the United Mine Workers and Operators.

	<i>Per Yard</i>
☐ Pick rate, 8-foot entries	\$1.82
12-foot entries	1.24
16-foot entries	0.00
Room turning	4.55
Machine rate, 8-foot entries	1.46
12-foot entries	1.00
16-foot entries	0.00
☐ Room turning	3.64

Items fixed by the experience of the company in the Fulton County Field.

Switch laying and ties	\$4.00 per room
Props	0.005 per square foot
Each prop costing \$0.06 and supporting an average of 12 square feet of roof.	
Wood rails, 1.3 times the length of the room at \$22.00 per 1000 board feet	6.25 for 180-foot room 7.45 for 210-foot room
Track laying and ties	0.10 per foot
Brushing and timbering entries, approximately \$3.00 per foot for 25 per cent of the length of the entry	0.75 per foot

Some of the figures given would not be applicable at present, but the method used can be applied by changing the expense of various items to correspond with changes in conditions.

In computing the production to be expected from different dimensions of workings, it is assumed that 25 cubic feet of coal in place are equivalent to one ton, and that 5.70 square feet of area are equivalent to a production of one ton if proper allowances are made for the thickness of the coal, which averages 4 feet, 10 inches, and for the waste which always accompanies mining. It is assumed that rooms from adjoining cross entries are driven through until they meet and that five cross-cuts are driven in the length of the two 180-foot rooms and six in the length of the two 210-foot rooms. This arrangement accounts for the average number of cross-cuts being $2\frac{1}{2}$ for a 180-foot room.

The following tables give the essential data on which the calculations are based. Table 8 gives the number of rooms in 160 acres, for each room width and for each pillar width, for rooms 180 feet long and 210 feet long. The total number of rooms varies less regu-

TABLE 8
NUMBER OF ROOMS IN 160 ACRES

Room Width (Feet)	Room Length and Centers	Pillar Width								
		6	7	8	9	10	11	12	16	20
20	180	1330	1298	1232	1204	1162	1120	1106	980	882
	Centers	26	27	28	29	30	31	32	36	40
	210	1140	1104	1056	1032	996	960	948	840	756
21	180	1298	1232	1204	1162	1120	1106	1050	952	840
	Centers	27	28	29	30	31	32	33	37	41
	210	1104	1056	1032	996	960	948	900	816	720
22	180	1232	1204	1162	1120	1106	1050	1036	938	840
	Centers	28	29	30	31	32	33	34	38	42
	210	1056	1032	996	960	948	900	888	804	720
23	180	1204	1162	1120	1106	1050	1036	994	896	826
	Centers	29	30	31	32	33	34	35	39	43
	210	1032	996	960	948	900	888	852	768	708
24	180	1162	1120	1106	1050	1036	994	980	882	784
	Centers	30	31	32	33	34	35	36	40	44
	210	996	960	948	900	888	852	840	756	672
25	180	1120	1106	1050	1036	994	980	952	840	784
	Centers	31	32	33	34	35	36	37	41	45
	210	960	948	900	888	852	840	816	720	672
26	180	1106	1050	1036	994	980	952	938	840	770
	Centers	32	33	34	35	36	37	38	42	46
	210	948	900	888	852	840	816	804	720	660

larly than the dimensions, because no fractional rooms were considered, but only such arrangements of whole rooms as would most nearly completely cover the 160-acre tract.

TABLE 9
AREA OF ROOMS¹ AND TONS OF COAL PER ROOM²

Width of Rooms (Feet)	Length 180 Feet		Length 210 Feet	
	Area (Square Feet)	Tons	Area (Square Feet)	Tons
20	3382	593.33	3982	698.60
21	3546.5	622.16	4176.5	732.32
22	3711	651.05	4371	766.84
23	3875.5	679.91	4565.5	800.96
24	4040	708.77	4760	835.08
25	4204.5	737.63	4954.5	869.20
26	4369	766.50	5149	903.33

¹Not including cross-cuts.

²25.70 square feet of 4-foot, 10-inch coal per ton, allowing for waste.

TABLE 10
AREA OF ROOM CROSS-CUTS (PER CROSS-CUT), TONS OF COAL PRODUCED AND YARDAGE COST¹

Width of Pillar (Feet)	8-ft. Cross-Cut			12-ft. Cross-Cut			16-ft. Cross-Cut		
	Area (Square Feet)	Tons of Coal at 5.70 Square Feet per Ton	Yardage Cost at 60½ cents per Foot	Area (Square Feet)	Tons of Coal at 5.70 Square Feet per Ton	Yardage Cost at 41½ cents per Foot	Area (Square Feet)	Tons of Coal at 5.70 Square Feet per Ton	Yardage Cost 0.00
6	48	8.41	\$3.64	72	12.62	\$2.48	96	16.84	.....
7	56	9.83	4.25	84	14.74	2.89	112	19.65	.....
8	64	11.23	4.85	96	16.84	3.31	128	22.46	.....
9	72	12.63	5.46	108	18.94	3.72	144	25.26	.....
10	80	14.03	6.07	120	21.05	4.14	160	28.07	.....
11	88	15.44	6.67	132	23.16	4.55	176	30.88	.....
12	96	16.84	7.28	144	25.66	4.96	192	33.68	.....
16	128	22.46	9.71	192	33.69	6.61	256	44.91	.....
20	160	28.07	12.13	240	42.10	8.27	320	56.14	.....

¹Yardage for narrow work, pick rate:

8 feet wide \$1.82 = 60½ cents per foot.

12 feet wide 1.24 = 41½ cents per foot.

16 feet wide 0.00 = 00 cents per foot.

Table 9 gives the areas of rooms, not including cross-cuts, and the tons of coal per room calculated on the basis of 5.70 square feet per ton.

Table 10 gives for each cross-cut the area, the tons of coal produced, and the yardage cost. The number of tons produced is calculated from the area on the basis of 5.70 square feet per ton. The yardage cost is calculated from the prices fixed in the agreement with the United Mine Workers. Only the rate for pick mining was considered as machines were not used much in the district when the data were compiled. The ratio between yardage cost for 8-foot and 12-foot cross-cuts is the same for pick work as for machine work; therefore if the rates for machine work were substituted in place of those for pick work in the calculations, the results would show a decrease in the total expense, but the percentage of the total expense for narrow work saved by the reduction in the amount of this work would remain the same. Three widths of cross-cuts were considered: 8 feet, which is assumed to be the minimum practical width (this is the minimum width for which a yardage price is fixed in the agreement with the United Mine Workers); 12 feet, which is considered an average; and 16 feet, which, according to the agreement, is wide work and does not require extra compensation.

TABLE 11
TOTAL CROSS-CUT YARDAGE COST PER ROOM

Width of Pillar (Feet)	8-ft. Cross-Cuts		12-ft. Cross-Cuts	
	180-ft. Room 2½ Cross-Cuts	210-ft. Room 3 Cross-Cuts	180-ft. Room 2½ Cross-Cuts	210-ft. Room 3 Cross-Cuts
6	\$ 9.10	10.92	6.20	7.44
7	10.63	12.75	7.23	8.67
8	12.13	14.55	8.28	9.93
9	13.65	16.38	9.30	11.16
10	15.18	18.21	10.35	12.42
11	16.68	20.01	11.38	13.65
12	18.20	21.84	12.40	14.88
16	24.28	29.12	16.53	19.84
20	30.33	36.39	20.67	24.80

Table 11 gives the total cross-cut yardage cost per room, obtained by multiplying the cost per cross-cut as given in Table 3 by the proper number of cross-cuts.

TABLE 12
TONS OF COAL IN CROSS-CUTS PER ROOM

Width of Pillar (Feet)	180-ft. Room 2½ Cross-Cuts		210-ft. Room 3 Cross-Cuts	
	8-ft. Cross-Cut	16-ft. Cross-Cut	8-ft. Cross-Cut	16-ft. Cross-Cut
6	21.02	42.04	25.23	50.46
7	24.58	49.16	29.49	58.98
8	28.07	56.14	33.69	67.38
9	31.57	63.14	37.89	75.78
10	35.08	70.16	42.09	84.18
11	38.60	77.20	46.32	92.64
12	42.09	84.18	50.52	101.04
16	56.15	112.30	67.38	134.76
20	70.17	140.34	84.21	168.42

TABLE 13
COST OF PROPS FOR ROOM AND CROSS-CUTS AT ONE-HALF CENT PER SQUARE FOOT, 180-FOOT ROOMS

Width of Room (Feet)	Prop Cost for Room	Width of Pillar								
		6	7	8	9	10	11	12	16	20
		Prop Cost for Cross-Cuts per Room								
		\$0.90	\$1.05	\$1.20	\$1.35	\$1.50	\$1.65	\$1.80	\$2.40	\$3.00
		Prop Cost for Room and Cross-Cuts								
20	\$16.91	\$17.81	\$17.96	\$18.11	\$18.26	\$18.41	\$18.56	\$18.71	\$19.31	\$19.91
21	17.73	18.63	18.78	18.93	19.08	19.23	19.38	19.53	20.13	20.73
22	18.56	19.46	19.61	19.76	19.91	20.06	20.21	20.36	20.96	21.56
23	19.38	20.28	20.43	20.58	20.73	20.88	21.03	21.18	21.78	22.38
24	20.20	21.10	21.25	21.40	21.55	21.70	21.85	22.00	22.60	23.20
25	21.02	21.92	22.07	22.22	22.37	22.52	22.67	22.82	23.42	24.02
26	21.85	22.75	22.90	23.05	23.20	23.35	23.50	23.65	24.25	25.85

Table 12 gives the amount of cross-cut coal in tons per room, obtained by dividing the areas of cross-cuts by 5.70, the number of square feet of area equivalent to a production of one ton, and multiplying by the proper number of cross-cuts per room.

TABLE 14

COST OF PROPS FOR ROOM AND CROSS-CUTS AT ONE-HALF CENT PER SQUARE FOOT, 210-FOOT ROOMS

Width of Room (Feet)	Prop Cost for Room	Width of Pillar								
		6	7	8	9	10	11	12	16	2
		Prop Cost for Cross-Cuts per Room								
		\$1.08	\$1.26	\$1.44	\$1.62	\$1.80	\$1.98	\$2.16	\$2.88	\$3.60
		Prop Cost for Room and Cross-Cuts								
20	\$19.91	\$20.99	\$21.17	\$21.35	\$21.53	\$21.71	\$21.89	\$22.07	\$22.79	\$23.51
21	20.88	21.96	22.14	22.32	22.50	22.68	22.86	23.04	23.76	24.48
22	21.86	22.94	23.12	23.30	23.48	23.66	23.84	24.02	24.74	25.46
23	22.83	23.91	24.09	24.27	24.45	24.63	24.81	24.99	25.71	26.43
24	23.80	24.88	25.06	25.24	25.42	25.60	25.78	25.96	26.68	27.40
25	24.77	25.85	26.03	26.21	26.39	26.57	26.75	26.93	27.65	28.37
26	25.75	26.83	27.01	27.19	27.37	27.55	27.73	27.91	28.63	29.35

Tables 13 and 14 give the cost of props for a room and its cross-cuts for each width of room from 20 to 26 feet and for each width of pillar from 6 feet to 20 feet. The cost in cents is obtained by dividing the cost per prop, taken as six cents, by the area supported by one prop, 12 square feet, these being figures based upon the experience of the company.

$$\frac{\text{Cost per prop}}{\text{Square feet of area supported}} = \frac{6}{12} = \frac{1}{2} \text{ cent per square foot, or for 1 room}$$

$$\frac{\text{Number of square feet in room}}{2} = \text{cost in cents}$$

In each table the cost of props per room is given at the left, the cost of props for cross-cuts is given at the top, and the cost of props for the rooms and cross-cuts together is given in the body of the table.

These tables of prop costs are computed on the assumption that all cross-cuts are 12 feet wide. In the comparison of total costs, this assumption introduces a small error because this comparison is between 8-foot and 16-foot cross-cuts. To obtain correct values it would be necessary to make allowance for the error thus introduced by

decreasing the prop cost with 8-foot cross-cuts and increasing it with 16-foot cross-cuts. The difference between these two costs would accordingly be decreased, this difference being the saving effected by the use of 16-foot cross-cuts. In rooms of 180 feet long with 6-foot pillars, the error introduced by the use of this average figure amounts to 94 cents per thousand tons. In rooms 210 feet long with 20-foot pillars, the error is \$2.09 per thousand tons. These errors are the extremes, and the errors when other dimensions of rooms and pillars are used lie between these two. Since the pillar width selected as the best was small,—viz., 8 feet, the effect of the assumption of 12-foot cross-cuts was small.

The specimen computations given show the methods employed. All essential data are contained in the preceding tables and the calculations involve only the arrangement of these data in such form as clearly to represent the facts and permit comparisons between percentages of extraction and costs of production for different dimensions of rooms.

SPECIMEN COMPUTATIONS

COAL PRODUCED

Rooms and Cross-Cuts

Room width	20 feet
Room length	210 feet
Pillar width	6 feet
Total number of rooms in 160 acres	1140
Room coal	698.60 tons
Coal from 8-foot cross-cuts	25.23 tons
Total coal from room and 8-foot cross-cuts	723.83 tons
Coal from additional 8-feet of cross-cuts	25.23 tons
Total coal per room and 16-foot cross-cuts	749.06 tons

Coal from 160 Acres

	<i>Tons</i>
Total room coal = $698.60 \times 1140 =$	796,404
Total coal from 8-foot cross-cuts = $25.23 \times 1140 =$	28,762
Coal from main entry and cross-cuts	16,716
Coal from cross entries and cross-cuts	47,836
Total	889,718
Additional coal from 16-foot cross-cuts	28,762
Grand total	918,480

COST AND SAVING

Fixed Room Charges per Room

Room turning	\$ 4.55
Switch-laying and ties	4.00
Wood rails	7.45
	\$16.00
Props per room and 8-foot cross-cut	21.00
	\$37.00
Room cross-cut yardage	10.92
Total for room and cross-cuts	\$47.92

Total Fixed Room Charges per 160 Acres

Room turning; switch laying and ties; wood rails, props = $\$37.00 \times 1140 =$	\$42,180.00
Room cross-cut yardage $10.92 \times 1140 =$	12,448.80
Total fixed room charges	\$54,628.80
Saving by making cross-cuts 16 feet wide	
. . . \$12,448.80 = 22.79 per cent fixed room charges with 8-foot cross-cuts	

Total Cost for Items Considered

Total fixed room charges	\$ 54,628.80
Main entry and cross-cuts,	
11,910 feet narrow work at \$0.61 per foot	7,265.10
Cross entries and cross-cuts,	
34,080 feet narrow work at \$0.61 per foot	20,788.80
Track laying	4,176.00
Brushing and timbering	31,320.00
Total cost for 160 acres	\$118,178.70
Total cost for 160 acres with 16-foot room cross-cuts,	
118,178.70 - 12,448.80 =	\$105,729.90

Cost per 1,000 tons with 8-foot room cross-cuts $\frac{118,178.70}{889.718} =$	132.83
Cost per 1000 tons with 16-foot room cross-cuts $\frac{105,729.90}{918.480} =$	115.11
Saving per 1000 tons with 16-foot room cross-cuts*	17.72

*The cost per 1000 tons mined is less by one method than by the other, but the quantity of coal considered is greater in the case of 16-foot room cross-cuts by the 28,762 tons gained in the additional 8 feet of cross-cut width.

The accompanying sets of diagrams, Figs. 12 and 13, show the most important points in connection with the percentage of extraction and the cost of production, so far as the latter is determined by the limited elements considered, for all room widths from 20 to 26 feet and for pillar widths of 6, 9, 12, 16, and 20 feet with 210-foot rooms and for 6-foot pillar widths with 180-foot rooms.

Three diagrams in each set are concerned with quantity of production. Diagram *A* gives the number of rooms in 160 acres; diagram *B*, the amount of coal produced per room and cross-cut; and diagram *C* the total amount of coal produced. This total production includes, not only coal taken from rooms and their cross-cuts, but also coal taken from entries and entry cross-cuts.

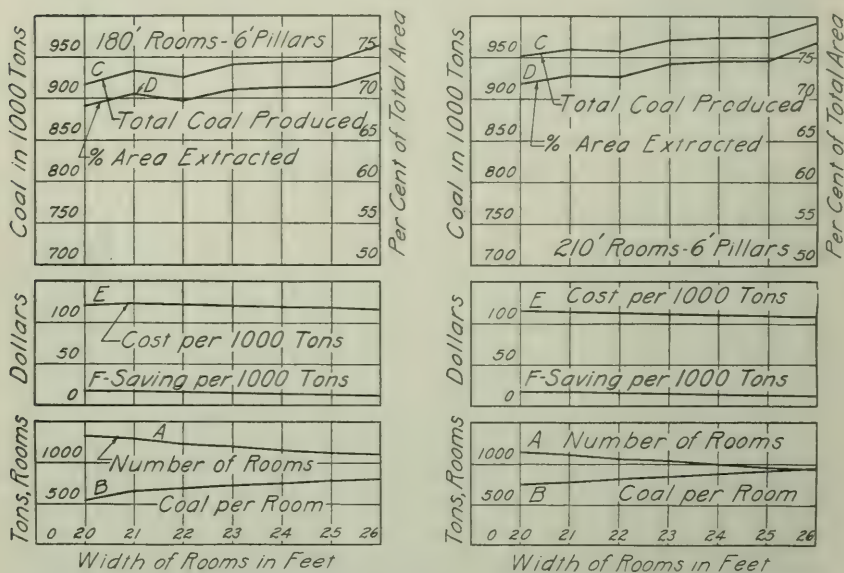


FIG. 12. NUMBER OF ROOMS PER ENTRY, COAL PER ROOM, TOTAL COAL FROM 160 ACRES, PERCENTAGE OF AREA EXCAVATED, COST PER 1000 TONS, SAVING PER 1000 TONS

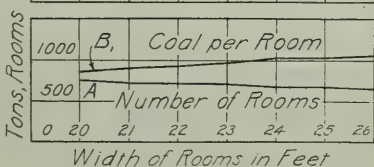
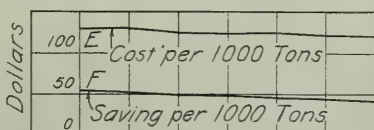
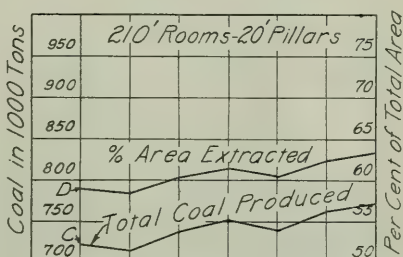
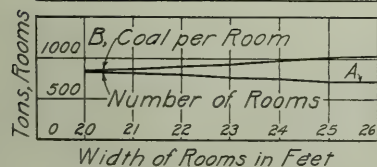
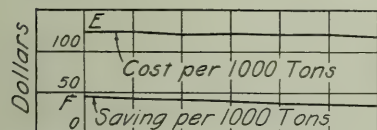
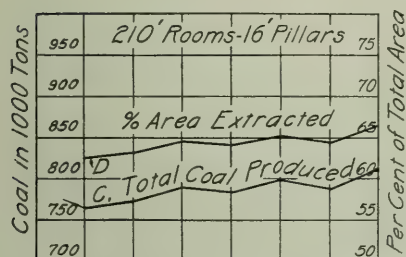
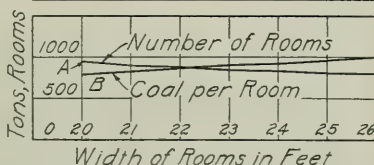
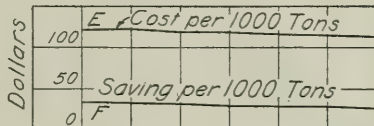
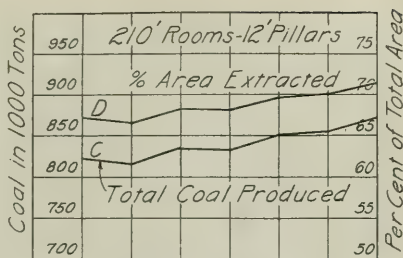
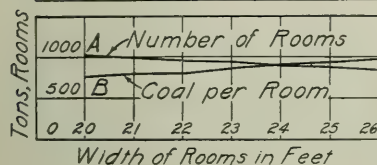
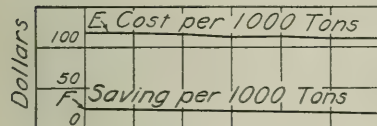
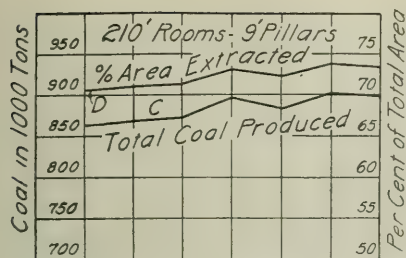


FIG. 13. NUMBER OF ROOMS PER ENTRY, COAL PER ROOM, TOTAL COAL FROM 160 ACRES, PERCENTAGE OF AREA EXCAVATED, COST PER 1000 TONS, SAVING PER 1000 TONS

Diagram *D* shows the percentage of extraction, based on the area excavated instead of on the number of tons produced as calculated by Mr. Quade, in order that this portion of the discussion may be brought into direct comparison with the preceding part of the bulletin. The values for the percentage of extraction on the area basis are slightly higher than they would be if computed from tonnage produced because of the waste in mining and the presence of slips and horse backs. If these losses did not exist, the values of the percentage of extraction obtained by the two methods would be the same, because the entire thickness of the coal bed is extracted. A comparison of these two methods in rooms 20 by 210 feet with 12-foot pillars and 16-foot cross-cuts gave an extraction on the basis of tons produced of 61.05 per cent and on the basis of area excavated of 67.28 per cent.

. The diagram for total output is irregular, because its shape is determined by that for the number of rooms. This number does not change uniformly with change of width of rooms, but, for each set of dimensions, the number of rooms was selected which was most suitable for working out the 160-acre tract to be developed. The total output is the sum of the tonnage of coal produced in rooms and cross-cuts, and in entries. Since the output from entries varies only with the number of cross entries which in turn is affected by a change in the length of rooms, the total output varies only with the number of rooms or with the output from a room and its cross-cuts. The latter quantity varies regularly with the change of room width, and therefore irregularities in the total output are entirely due to irregularities in the number of rooms. The curve for total output is drawn to a scale which makes its irregularities more prominent than those in the curve for the number of rooms.

Diagram *E* shows the cost per thousand tons for the limited number of items considered. The line drops as that showing total output rises, thus showing that the cost of production decreases as the output from a given area increases.

Diagram *F* shows the saving per thousand tons accomplished by increasing the width of room cross-cuts from 8 feet to 16 feet, and eliminating room cross-cut yardage. Mr. Quade's computations were made with the object of determining this saving, and the adoption of the dimensions indicated by these calculations as being most economical has resulted in very large reduction in the cost of producing coal.

The dimensions selected were: room width 24 feet, pillar width 8 feet, cross-cut width 16 feet. The diagrams show that the cost would be lower and the extraction higher if narrower pillars could be used, but it was not practical to make them less than about 8 feet in width. This width is, however, necessary only near the entries; the pillars are made gradually narrower towards the ends of the rooms, the percentage of extraction being thus increased. The extraction in these mines since the adoption of the new dimensions is between 70 and 75 per cent.

For purposes of comparison one set of diagrams is given which shows, for 180-foot rooms, the same items of production and cost as are given for 210-foot rooms. At the time when the computations were made rooms were being driven 180 feet long. The total output for the two lengths of rooms differs only slightly, but the cost of production is lower with the 210-foot room; hence that length was adopted as a standard.

The diagrams in Fig. 14 show the production of coal from different parts of the workings and emphasize the increase of production with increase of room width. Diagram *A* shows the production from rooms and 8-foot cross-cuts. Diagram *B* shows the sum of the tonnage of room and cross-cut coal and entry coal, the space between *A* and *B* representing the entry coal. The space between *B* and *C* shows the additional coal taken from 16-foot cross-cuts; therefore *C* shows the total coal produced from 160 acres with the longer dimension.

Fig. 15 is a graphical summary of costs and output for rooms 24 feet wide and 210 feet long. Diagrams *A*, *B*, *C*, and *D* show the effect of increase of pillar width on the tonnage produced. On these diagrams, *A* shows the number of rooms in 160 acres; *B* shows the output from rooms and 8-foot cross-cuts; *C* shows the additional output from entries; and *D* shows the additional output from the extra width of room cross-cuts. The diagram shows the decrease of output resulting from the decrease in the number of rooms, which accompanies increase of pillar width.

The items of cost considered in the investigation are shown in zones, of which the first is yardage cost for the main entry, the second yardage cost for the cross entries, the third track-laying cost for entries, the fourth brushing and timbering costs for entries, the fifth fixed room charges, and the sixth yardage cost of 8-foot room cross-cuts.

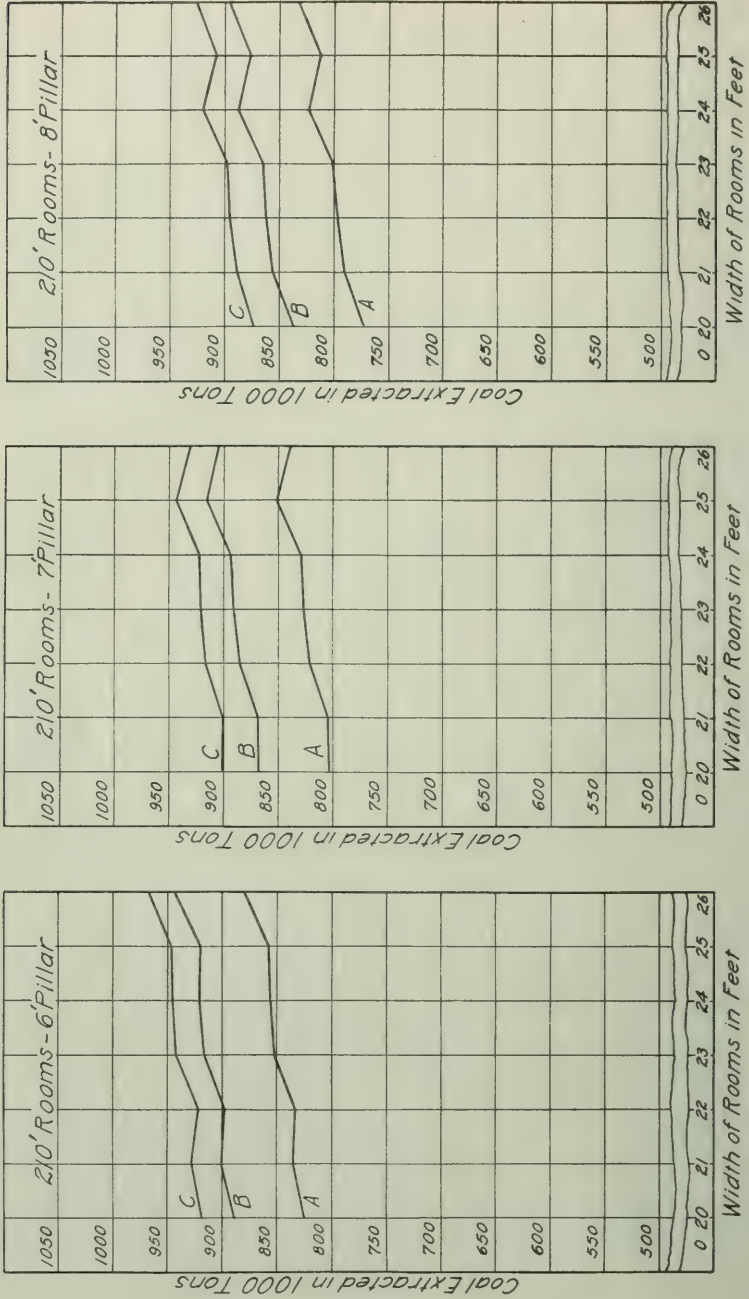
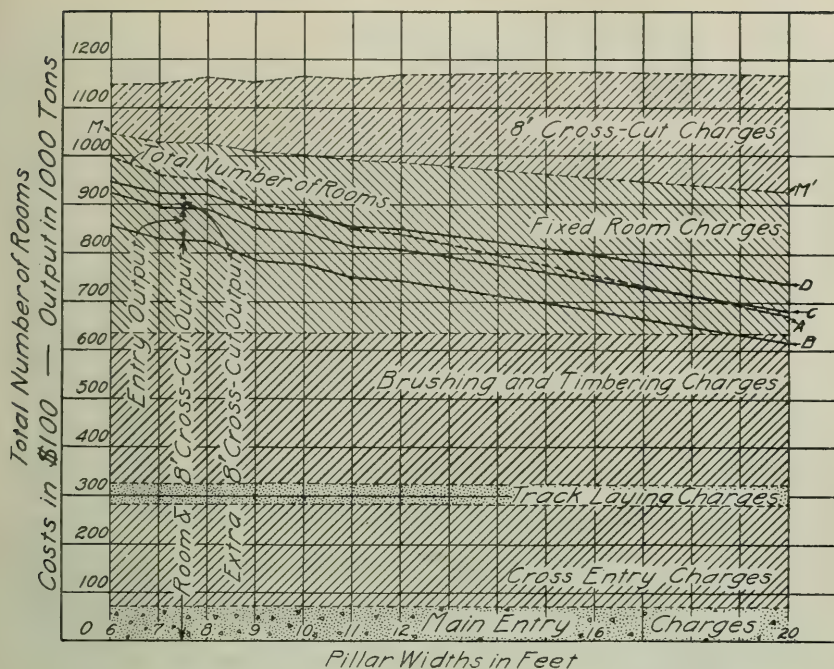


FIG. 14. PRODUCTION FROM ROOMS, ENTRIES, AND FROM ADDITIONAL CROSS-CUT WIDTH



The first four items change only when change in the length of rooms results in change of number of cross entries and therefore of total length of entries. The fifth item, fixed room charges, includes room turning, switch laying and ties, wood rails, and room props. The first three subdivisions change only with the number of rooms; the last increases with the width of rooms but decreases with their number. The sixth item, yardage cost of 8-foot cross-cuts, increases with pillar width because of the increased length of the cross-cuts. It is this last item of cost which is eliminated by increase of cross-cut width to 16 feet, leaving the line M M' as the indication of total cost.

Some of the charts prepared by Mr. Quade are reproduced with some modification in Figs. 16, 17, and 18 to show more fully his method of presenting his conclusions.

Fig. 16 shows the effect of changes in cross-cut width on yardage cost for room cross-cuts and the amount of coal produced from

them. The diagrams are based on 7-foot pillars with three cross-cuts per pillar. The arrangements of cross-cut widths in each pillar are: three 8 feet wide; one 8 feet and two 12 feet; three 12 feet; one 8 feet, one 12 feet, and one 16 feet; two 12 feet and one 16 feet; one 12 feet and two 16 feet, and three 16 feet. In the final computation of possible reductions of cost the only widths considered were 8 feet and 16 feet.

Fig. 17 gives in detail the cost per thousand tons as modified by certain changes in length and width of rooms, room pillars, entries, and room and entry cross-cuts.

The width of rooms considered, 25.36 feet, was the actual average made by 8 cuts of a breast-type chain coal cutting machine. This machine is commonly called a 3-foot machine, but the actual cut slightly exceeded this width. The costs of the various items considered are shown by the widths of the shaded bands, while the solid line *AB* shows the saving per thousand tons accomplished by the use of the

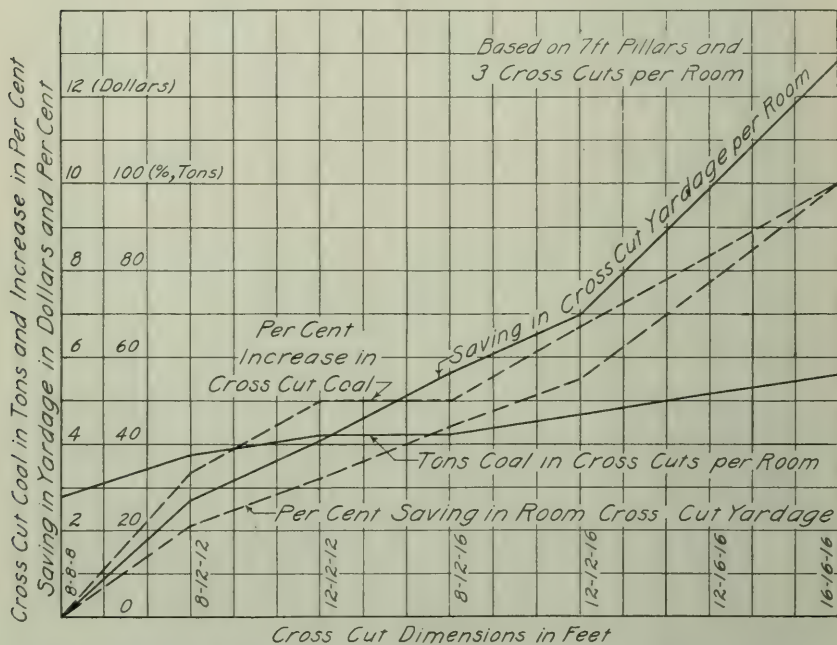


FIG. 16. EFFECT OF CHANGES IN CROSS-CUT WIDTH ON COST OF CROSS-CUTS AND COAL PRODUCED

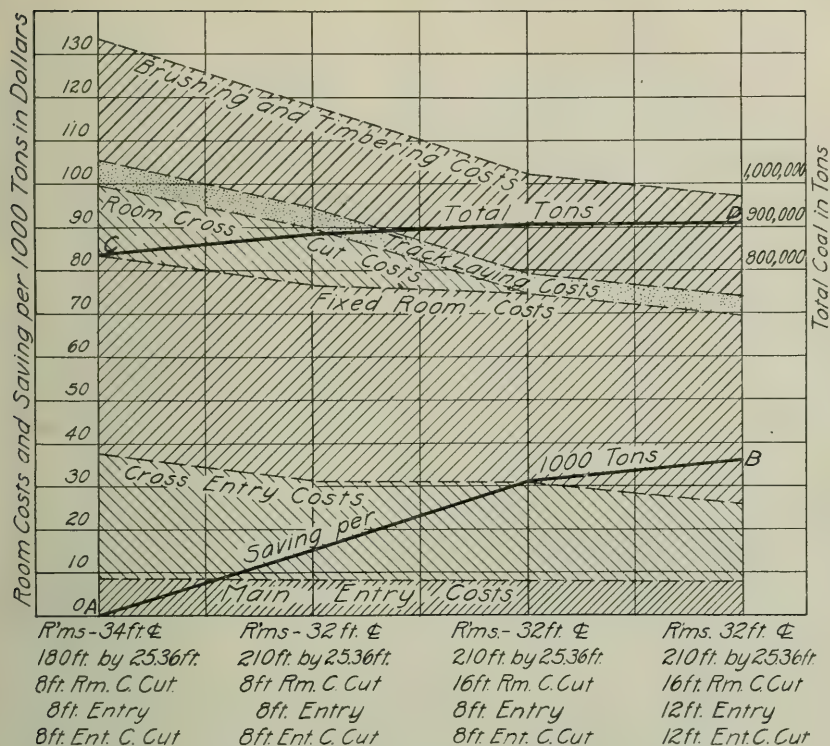


FIG. 17. CERTAIN FIXED CHARGES PER 1000 TONS, SAVING PER 1000 TONS, TOTAL OUTPUT FROM 160 ACRES

different changes in dimensions specified. The solid line *CD* shows the total coal produced from 160 acres with the same dimensions.

Fig. 18 is a summation of the items of room and room cross-cut costs considered and of total extraction and cost for 160 acres. This figure permits comparisons between results obtained by using different dimensions and shows the point of lowest cost and highest extraction. As in Fig. 14, room widths of 22.2 feet and 25.36 feet are due to the width of cut of the breast-type of coal cutting machines. The lower shaded areas show the cost per room for the various items considered as fixed room charges. Room turning and switch costs per room are not affected by any changes of dimensions. Wood rail cost increases with the length of rooms. Prop cost increases with both length and width of rooms. Cross-cut yardage cost is affected by room length,

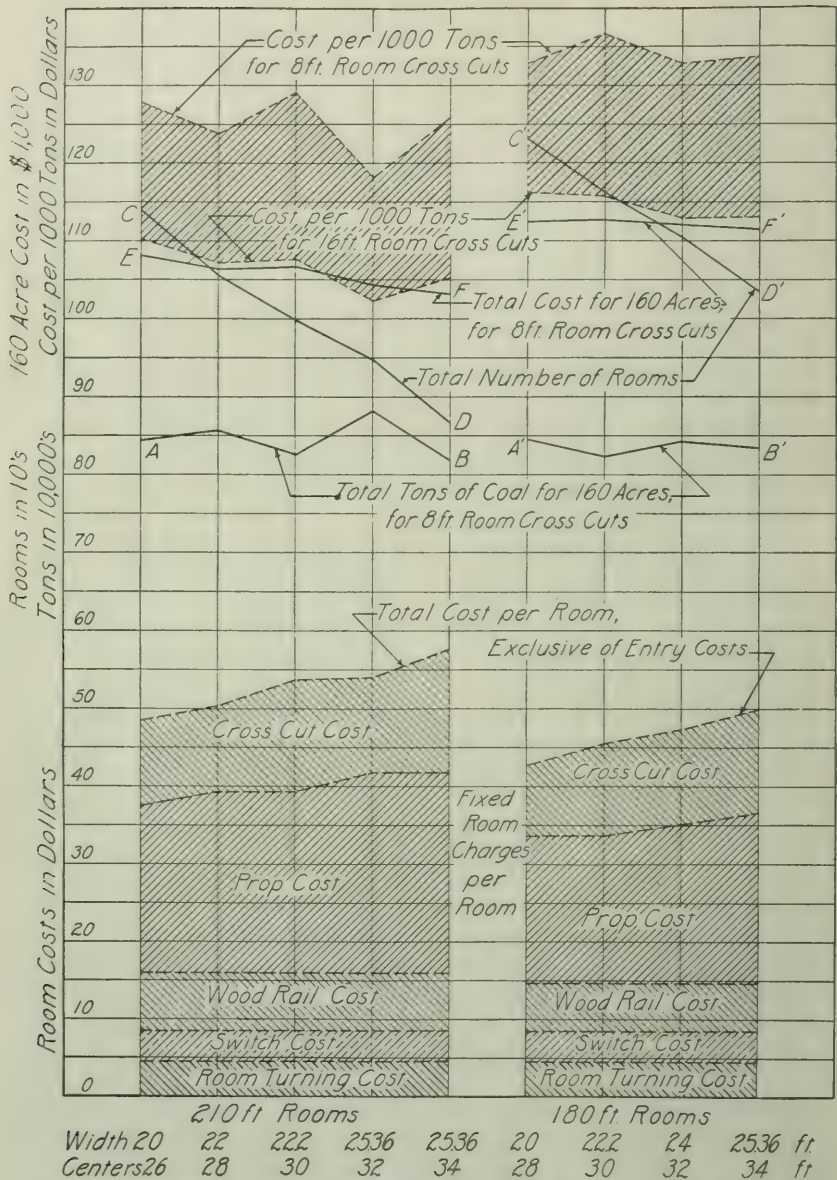


FIG. 18. SUMMATION OF FIXED CHARGES AND OUTPUT FOR 160 ACRES

which determines the number of cross-cuts, by cross-cut width and pillar width. The upper shaded areas show the difference in total cost per thousand tons, including entry costs, which results from the use of 8-foot and 16-foot room cross-cuts. The solid lines AB and $A'B'$ show the total coal produced from 160 acres; CD and $C'D'$ show the number of rooms in 160 acres; EF and $E'F'$ show the total cost for 160 acres when 8-foot cross-cuts are used.

The lowest total cost for 160 acres is shown to be reached with 210-foot rooms 25.36 feet wide on 34-foot centers, but the lowest cost per thousand tons and the highest extraction for 160 acres are shown to be reached with rooms of the same dimensions on 32-foot centers. Because of the common tendency of the miner to make his room somewhat wider than is planned, the latter dimensions might be approximately reached in practice if rooms were planned 24 feet wide on 32-foot centers. These dimensions, shown by Mr. Quade's work to be the best, were adopted for the company's mines in Fulton County with the result that the cost of producing coal was materially reduced. The percentage of extraction was raised from about 58 per cent to between 70 and 75 per cent which is unusually high for Illinois.

APPENDIX II

EXTRACTION AT DEWMAINE

WORK OF G. E. LYMAN

The results obtained with different dimensions of rooms in the Williamson County mines of the Madison Coal Corporation are shown in the following sketch and notes prepared by G. E. Lyman, formerly Chief Engineer and now General Superintendent of that company, and are published here with his courteous permission. The sketch, Fig. 19, shows the plan of operation followed at Dewmaine, north of Cartersville. The only changes from the dimensions shown are in the width of room pillars, the two widths being 20 feet and 14 feet. The plans considered and compared, with each pillar width, involve the extraction of different quantities of pillar coal after the rooms have been finished.

The area considered is a restricted one, consisting only of a cross entry and a portion of the rooms turned from it. The tract con-

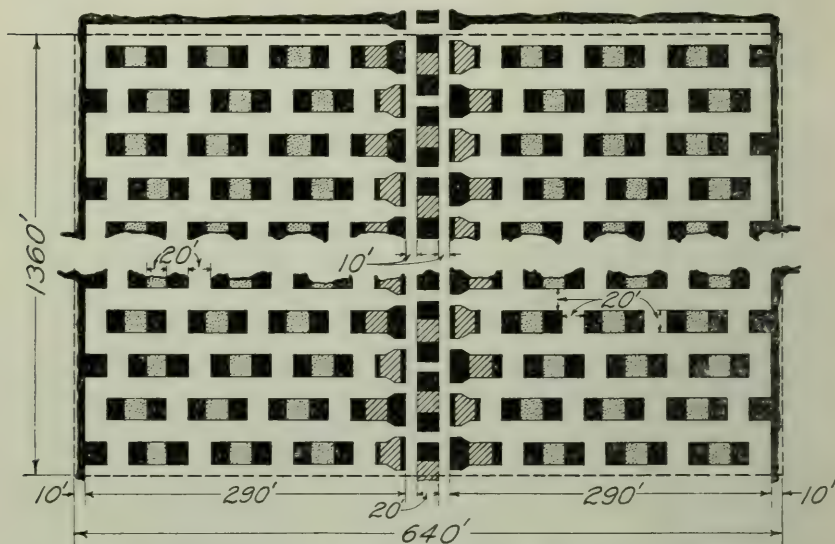


FIG. 19. DIMENSIONS OF ROOMS AND CROSS ENTRIES AT DEWMAINE

sidered is 640 feet wide by 1360 feet long and has an area of 870,000 square feet.

The following notes give the results of experience with different dimensions of rooms and the extraction of different amounts of pillar coal. With each of the two pillar widths different amounts of coal were extracted. With rooms 20 feet wide on 40-foot centers, plan No. 1, shown in white, gave the following extractions:

	<i>Square feet</i>
Rooms	$68 \times 5725 = 389,300$
Cross-cuts	$4 \times 68 \times 400 = 108,800$
Entries	$2 \times 10 \times 1360 = 27,200$
Entry cross-cuts	$21 \times 200 = 4,200$
Total area excavated	(60.7 per cent) 529,500

The experience of the company thus far indicates that workings with these dimensions will stand indefinitely except where soft mud or quicksand predominates in the cover.

Plan No. 2 involves the driving of additional cross-cuts in the room pillars after the room has been completed. These additional cross-cuts are shown by the dotted areas in the figure. The additional area extracted is:

$$3 \times 68 \times 400 = 81,600 \text{ square feet}$$

Total area excavated (70.2 per cent) 611,100

Experience indicates that squeezing will occur in rooms, but that the entry stumps will protect the entry so that it will not be closed. More or less water will follow the squeeze. The surface will subside gently to a depth of 2 feet to 4 feet in the center of the area.

Plan No. 3 involves the driving of additional cross-cuts in the room stumps and chain pillar, while retreating, as shown by the hatched areas. The additional area excavated is:

	<i>Square feet</i>
Room cross-cuts	$68 \text{ feet} \times 400 \text{ feet} = 27,200$
Entry cross-cuts	$20 \text{ feet} \times 400 \text{ feet} = 8,000$
Total area excavated	(72.4 per cent) 646,300

The results, as far as subsidences are concerned, are practically the same as those obtained by following plan No. 2, except that the entry is closed by the squeeze and more water enters the mine. The surface subsidence is practically the same as in plan No. 2.

Plans Nos. 4, 5, and 6 apply to the same method of working, but with room pillars only 14 feet wide which make 80 rooms in a block 640 feet by 1360 feet.

Plan No. 4 involves excavation of the following areas:

	<i>Square feet</i>
Rooms	$80 \times 5725 = 458,000$
Room cross-cuts	$80 \times 4 \times 280 = 89,600$
Entries	$2 \times 10 \times 1360 = 27,200$
Entry cross-cuts	$21 \times 200 = 4,200$
Total area excavated	(66.5 per cent) 579,000

When this plan is followed, squeezing occurs in a room a few months after the first working and more or less water enters the mine. The surface subsidence is about the same as in plan No. 2.

Plan No. 5 involves the driving of additional cross-cuts, as in plan No. 2, and the additional area excavated is:

	<i>Square feet</i>
Cross-cuts	$3 \times 80 \times 280 = 67,200$
Total area excavated	(74.2 per cent) 646,200

The results are practically the same as those obtained by following plan No. 2, except that more water enters the mine and the subsidence of the surface is deeper.

When additional cross-cuts are driven in room and entry re-treating, as shown by the hatched areas, in plan No. 6, the additional areas excavated are:

	<i>Square feet</i>
Room cross-cuts	$80 \text{ feet} \times 280 \text{ feet} = 22,400$
Entry cross-cuts	$20 \text{ feet} \times 400 \text{ feet} = 8,000$
Total area excavated	(77.7 per cent) 676,600

In this case the entire area squeezes, and a large quantity of water enters the mine. The surface subsidence extends over the whole area and is greater than with any of the other plans.

In the Dewmaine fields it has not been found practical to apply any plan except No. 1 until a considerable portion of the mine is ready for abandonment. Slight changes in the projection, however, are made when changes in physical conditions make them

advisable. Rooms are driven 20 feet wide, but pillars are sometimes reduced to 18 feet and entries are made either 10 or 12 feet wide.

In this field a great deal of trouble has been caused by the entry of water whenever the extraction of too much coal disturbed the overlying strata. Since plan No. 1 alone permits the indefinite sustaining of the overlying material, it is the only one which can be followed without entailing a great expense for handling water. Extraction is therefore limited to about 60 per cent of the panels or blocks, and must be considerably less when considering the whole mine. The calculated percentages of extraction given on page 34 for rooms and pillars of the same ratio of width,—namely, 25-foot rooms with 25-foot pillars, indicate that the total extraction is about 10 per cent less than the extraction in the panel area. It is therefore probable that the total amount of coal extracted in the mine as a whole is about 50 per cent. At various times plans No. 2 and No. 3 have been tried in limited areas, but trouble has always been caused by squeezes and inflow of water.

At the present time mining at No. 8 has proceeded far enough to permit the application of plan No. 3 in working from the boundary toward the shaft. The additional recovery will probably make the total extraction for the entire mine about 60 per cent.

Mr. Lyman points out that both the depth of cover and the nature of the ground vary considerably within short distances in the district referred to and that different results might be obtained within a short distance of the mine mentioned.

APPENDIX III

WORK OF J. C. GIBSON

J. C. Gibson of the Standard Engineering Company of Duquoin has developed a method for calculating the percentage of extraction and the future life of a mine by which it is possible to indicate the parts of the workings in which the losses occur. The following description of procedure is published through the courtesy of Mr. Gibson.

When this method is applied, a tracing of the workings is made showing the outlines of groups of rooms, entries, barrier pillars, and lost areas. In the tracing these separate portions are given distinctive colors in order to prevent any possible confusion. Each area is then measured. This measurement can best be done with a planimeter, but very close approximation to the correct areas can be attained by measuring with a scale, especially if the outlines are not very irregular.

The application of this method to a part of a mine is shown in Fig. 20. The sums of the areas of the different portions in the entire mine are as follows:

<i>Areas worked out (Acres)</i>		<i>Percentage of Total Area</i>
Rooms and pillars	157.16	59.76
Entries	62.40	23.73
Lost coal	3.44	1.30
Barriers	40.00	15.21
Total area covered by workings, with exception of the shaft pillar		263.00
		100.00
		<i>Tons</i>
Room coal produced		1,421,023
Entry coal produced		378,744
Total coal produced, not including coal taken from the shaft pillar in driving the bottom		1,799,767

The tonnage produced from entries was calculated from the length, width and height of the entries and the weight of the coal per cubic foot, a method permissible when entries are driven with

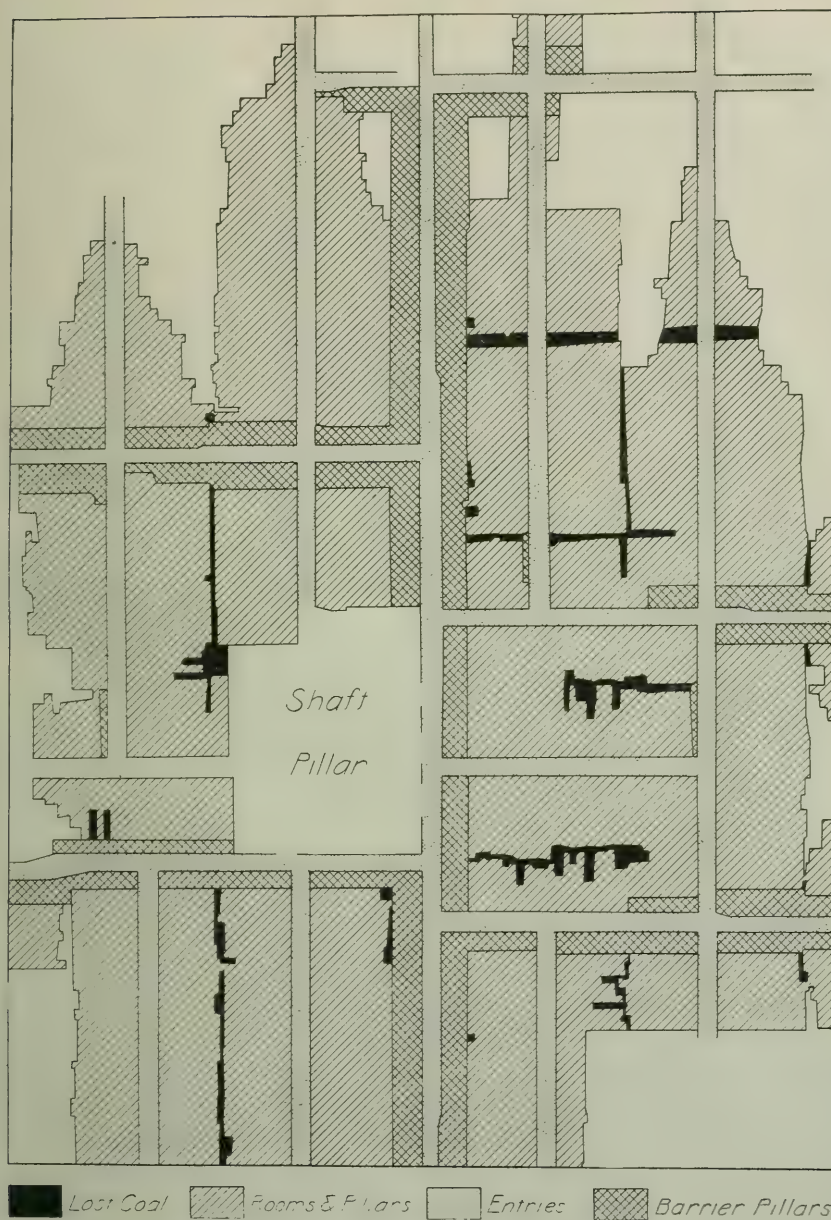


FIG. 20. PORTION OF MINE AS MAPPED BY J. C. GIBSON

careful adherence to the projected dimensions. The tonnage produced from other workings is the difference between total output and entry coal.

The average thickness of coal being 9.4 feet and the weight per cubic foot 81.25 pounds, the amount of coal originally present per acre was

$$\frac{43,560 \times 9.4 \times 81.25}{2,000} = 16,634 \text{ tons}$$

The area worked over by rooms and pillars is 157.16 acres. The coal originally present in the room and pillar area was $157.16 \times 16,634 = 2,614,199$ tons; and the percentage of extraction in the territory occupied by rooms and pillars was

$$\frac{1,421,023 \times 100}{2,614,199} = 54.36 \text{ per cent}$$

The entries occupied 62.40 acres, and the coal originally present was $62.40 \times 16,634 = 1,037,961$ tons. The percentage of extraction in territory occupied by entries was

$$\frac{378,744 \times 100}{1,037,961} = 36.49 \text{ per cent}$$

The coal originally present in the whole area was $263 \times 16,634 = 4,374,742$ tons and the percentage of extraction over the whole area worked out was

$$\frac{1,799,767 \times 100}{4,374,742} = 41.14 \text{ per cent}$$

Since the thickness of the bed is 9.4 feet and the height of entries only 7 feet, the percentage of area excavated in entries is $\frac{9.4}{7}$ of the percentage of coal extracted.

$$\frac{9.4}{7} \times 36.49 \text{ per cent} = 49.00 \text{ per cent}$$

The data given do not provide a basis for the calculation of percentage of area worked out in the room-and-pillar blocks, because some of the top coal was taken. If no top coal had been taken, the

percentage of area worked out in the seven feet of coal being mined would be equal to the percentage of coal produced from that seven feet. The amount of coal originally present in the areas occupied by rooms and pillars in a thickness of seven feet was

$$\frac{43,560 \times 7 \times 81.25 \times 157.16}{2000} = 1,946,799 \text{ tons}$$

As the coal taken out from these areas was 1,421,023 tons, the percentage of area excavated would have been 73.0 per cent if a thickness of only seven feet had been worked.

$$\frac{1,421,023 \times 100}{1,946,799} = 73.0 \text{ per cent}$$

If all the top coal had been taken down to a height of 9.4 feet, the percentage of area worked out would be the same as the percentage of coal produced when the thickness of 9.4 feet is considered,—that is, 54.36 per cent. Since some top coal was left, the percentage of area worked out must have been greater than 54.36 per cent and less than 72.2 per cent in order to give this percentage of extraction; however there are no data from which accurately to calculate the percentage.

In some mines where the only “solid” coal produced is top coal, all the remainder being known as “machine” coal, it would be possible to get from the books of the coal company the number of tons of solid coal paid for,—that is, the top coal. Then the percentage of area worked out in rooms could be determined from the tonnage produced.

It is claimed by Mr. Gibson that given the data on a number of mines in the preceding form, comparisons may be made and possibly much valuable information obtained. For example, mines in which a high percentage of extraction had been obtained in the room-and-pillar areas would indicate the practice to be followed in planning a new operation, provided, of course, that the history of those mines showed their practice to be satisfactory; mines in which the smallest percentage of coal had been lost in barrier pillars, provided the barriers had proved sufficient, would indicate the dimensions of barriers for use in new operations; and mines having the smallest ratio of entry area to room area would suggest efficient methods of developing a property.

Thus, from a number of plans of actual operations, might be developed a composite plan more efficient than any of those studied. It is evident that the two sets of percentages, those of the entire coal seam and those of the number of feet of the seam worked, will enable comparisons to be made with most of the properties studied.

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- Bulletin** 2. Coal Mining Practice in District VIII (Danville), by S. O. Andros. 1913. *None available.*
- Bulletin** 3. Chemical Study of Illinois Coals, by S. W. Parr. 1916. *Twenty-five cents.*
- Bulletin** 4. Coal Mining Practice in District VII (Mines in bed 6 in Bond, Clinton, Christian, Macoupin, Madison, Marion, Montgomery, Moultrie, Perry, Randolph, St. Clair, Sangamon, Shelby, and Washington counties), by S. O. Andros. 1914. *Free upon request.*
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- Bulletin** 9. Coal Mining Practice in District III (Mines in beds 1 and 2 in Brown, Calhoun, Cass, Fulton, Greene, Hancock, Henry, Jersey, Knox, McDonough, Mercer, Morgan, Rock Island, Schuyler, Scott, and Warren counties), by S. O. Andros. 1915. *Free upon request.*
- Bulletin** 10. Coal Resources of District I (Longwall), by G. H. Cady. 1915. *Twenty-five cents.*
- Bulletin** 11. Coal Resources of District VII (Counties listed in Bulletin 4), by Fred H. Kay. 1915. *None available.*
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- Bulletin** 16. Coal Resources of District II, by G. H. Cady. 1917. *Fifteen cents.*
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- Bulletin** 18. Tests on Clay Materials Available in Illinois Coal Mines, by R. T. Stull and R. K. Hursh. 1917. *Mailing weight, one pound.*
- Bulletin** 20. Carbonization of Illinois Coals in Inclined Gas Retorts, by F. K. Ovitiz. 1918. *Postage two cents.*
- Bulletin** 21. The Manufacture of Retort Coal-Gas in the Central States, Using Low-Sulphur Coal from Illinois, Indiana, and Western Kentucky, by W. A. Dunkley and W. W. Odell. 1918. *Postage two cents.*
- Bulletin** 22. Water-Gas Manufacture with Central District Bituminous Coals as Generator Fuel, by W. W. Odell and W. A. Dunkley. 1918. *Postage two cents.*
- Bulletin** 23. Mines Producing Low-Sulphur Coal in the Central District, by G. H. Cady. 1919. *Postage two cents.*
- Bulletin** 24. Water-Gas Operating Methods with Central District Bituminous Coals as Generator Fuel, by W. A. Dunkley and W. W. Odell. 1919. *Postage two cents.*

*Bulletin 72. U. S. Bureau of Mines. Occurrence of Explosive Gases in Coal Mines, by N. H. Darton. 1915. *Thirty-five cents.*

*Bulletin 83. U. S. Bureau of Mines, The Humidity of Mine Air, by R. Y. Williams. 1914. *Ten cents.*

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*Bulletin 102. U. S. Bureau of Mines, The Inflammability of Illinois Coal Dusts, by J. K. Clement and L. A. Scholl, Jr. 1916.

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*Copies may be obtained by addressing the Director, U. S. Bureau of Mines, Washington, D. C.

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CORONA DISCHARGE

BY

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WITH

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CORONA DISCHARGE

CHAPTER I

INTRODUCTION

1. *Statement of the Phenomenon.*—When high potential differences exist between conductors, the insulating property of the surrounding air partially breaks down, and a conduction of electricity through the air takes place, usually accompanied by a glow at either one of the conductors or in the intervening space. This glow is called the corona. The phenomenon is commonly seen when static machines or Tesla coils are operated in the dark, and less frequently from the tips of lightning rods during an electric storm. The corona is evident at night as it surrounds very high voltage alternating current transmission lines. The conduction represents a loss of power, which on long lines may become an important item. Peek (1), Whitehead (2), and others (3) have carefully studied this phenomenon for alternating differences of potential. In 1912, Peek (4), by a stroboscopic method, showed that there is a difference between the corona discharge from positive and negative conductors. This difference shows that corona caused by alternating potentials is a combination of two effects; and in order to study these effects separately and thus to learn the true facts concerning the phenomenon, continuous potentials must be used. A study of the corona caused by continuous potentials may produce engineering data of value owing to the increasing development of high tension direct-current generation and transmission. Previous to 1914, Watson (5) and Schaffers (6) were the only men who had experimented on the direct current corona.

Because of the desirability of a greater knowledge of the direct current corona, the Physics and Electrical Engineering Departments of the University of Illinois determined to carry out detailed research to develop a satisfactory theory for the corona phenomena. It is the purpose of this bulletin to present the results of the research which has been completed during the last few years.

Note.—The numbers within parentheses refer to the bibliography, page 131.

2. *Acknowledgments.*—The writers desire it to be clearly understood that the research presented in this bulletin is a compilation of the work done by the following, FARWELL, CROOKER, DAVIS, BREESE, OWENS, ANDEREGG, FAULKNER, and WARNER, under the direction of JAKOB KUNZ. The work of these men, as recorded in theses or in published articles, forms the basis of this bulletin. In many instances in order that statements might be accurate the words of the authors have been copied directly.

3. *Apparatus.*—The continuous voltage used in these investigations was obtained by means of a battery of forty, 500-volt, 250-watt, continuous-current, shunt-wound generators connected in series.

These machines are divided into two sets of ten machines each, and one set of twenty machines, each set being driven by a belt-connected, continuous-current shunt motor. The generators are mounted on insulating bases and the shafts of the separate machines are connected by insulating couplings. One terminal of each machine is permanently connected to its own frame in order definitely to limit the electrical strain on the machine insulation to the voltage generated by one armature.

The field of each generator is connected directly across the armature terminals, a single pole knife switch being included in the circuit in order that the machine may either be made to generate or to run idle at will. These switches were operated by means of a hard rubber rod approximately eighteen inches in length, since they may be twenty thousand volts above earth potential. The generators were run somewhat below rated speed in order to limit, to a safe value, the voltage generated without external resistance in the field circuit. The voltage of the machine supplying current to the driving motors was maintained at a constant value by means of a voltage regulator. The constant speed of the driving motors thus produced caused the resultant high potential of the battery of generators to be practically constant. A fine adjustment of voltage was obtained by means of a rheostat in the field circuit of one of the generators. Fig. 1 is a general view of the generating plant.

Most of the experimenters working in this field have dealt with corona in air. Air, however, changes in chemical composition immediately upon the formation of the corona, so that if accurate data are desired within the corona discharge region some arrangement

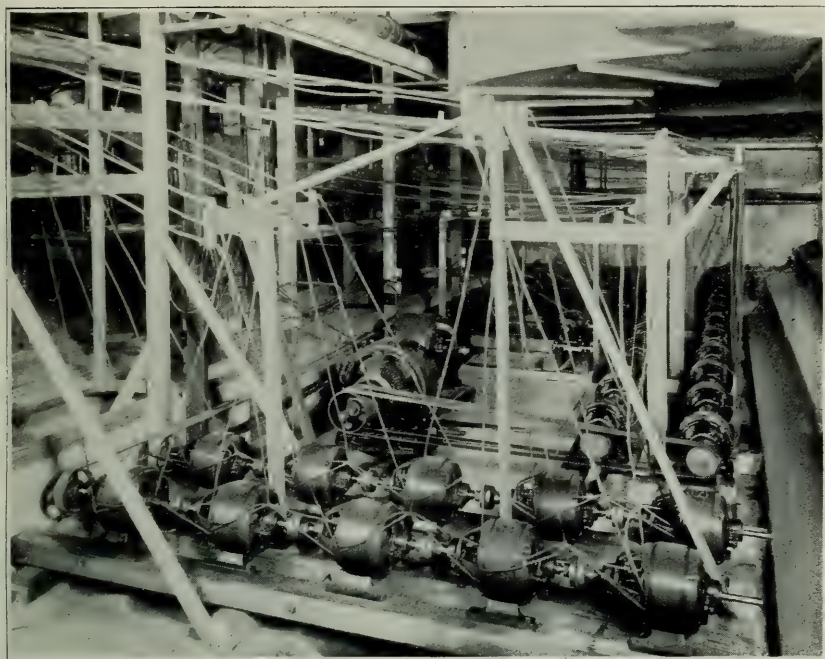


FIG. 1. GENERAL VIEW OF GENERATING PLANT

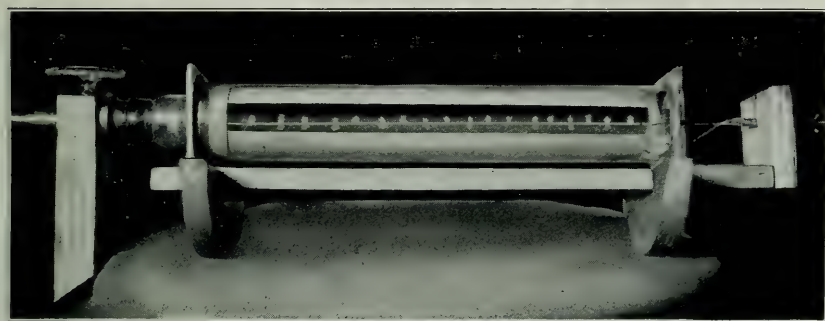


FIG. 2. A TYPICAL TUBE, WITH SLOT

must be made to insure uniformity of chemical structure in the dielectric at all times. Such uniformity is often accomplished by replacing the gas immediately surrounding the conductors as fast as its composition changes. This renewal is often impracticable.

To add to the knowledge of the corona in a substance which probably does not change chemically, experiments have been performed with chemically pure hydrogen as the dielectric. The hydrogen used in this part of the work was produced by the action of hydrone, a commercial alloy of lead and sodium, upon water. The reaction of the sodium with the water produces hydrogen, the lead acting as a retarding agent only. The hydrogen was collected over water and purified as used.

The purifying process consisted in forcing the hydrogen through concentrated sulphuric acid drying bottles placed in series with a calcium chloride tube, and then through a tube in a combustion furnace which contained red hot metallic calcium. The drying agents removed all water vapor and the heated calcium removed all traces of oxygen and nitrogen. Immediately after purification the hydrogen was conducted into the corona apparatus. In the purification of the hydrogen a discharge tube was connected directly to the corona apparatus, and the purity of the hydrogen was tested with a Hilger spectroscope. After careful purification no traces of any other gas than hydrogen were visible in the bright line spectrum.

The type of the corona discharge tube, used in most of the experiments to be described, was a cylinder with a wire strung along its axis. This type of tube was chosen for several reasons:

- (1) The corona phenomena, occurring when this type of apparatus is used, lend themselves peculiarly well to mathematical analysis.

- (2) The construction, manipulation, operation, and repair of the apparatus are extremely simple.

- (3) The field distribution is symmetrical with respect to the wire, and any irregularities in the wire are immediately recognizable in the discharge.

- (4) This type of apparatus has been used by other investigators; thus results could be compared with greater assurance of reliability.

The apparatus was so arranged that wires of different sizes could be easily strung and held taut exactly along the axis of the cylinder. In order to limit the length of the wire from which the discharge took place, glass plates with holes for the wire to pass through were sealed to the ends of the cylinder so that the holes were on the axis of the cylinder and metal bushings were inserted in these holes. The wire which was run through the bushings was held taut by sealing wax. The cylinder was provided with a side tube through which the air could be pumped out and dry air or pure gases allowed to enter. When the visible character of the corona was to be studied and photographed, the metal cylinder was provided with a longitudinal slot and the whole tube placed in a glass cylinder. Fig. 2 shows a typical tube with slot.

The voltages, if low, were measured with a Braun type Kohl electrostatic voltmeter, and, if higher, a vertical type Kelvin electrostatic voltmeter, having ranges of 5,000, 10,000, and 20,000 volts, was used. Frequently these instruments were calibrated by means of an attracted disk electrometer. In computing the voltages from the disk electrometer the end correction as treated by Maxwell (7) was applied.

Currents were measured by means of a d'Arsonval galvanometer and an Ayrton universal shunt. These were calibrated as a unit by connecting them in series with a high resistance and a dry cell, the

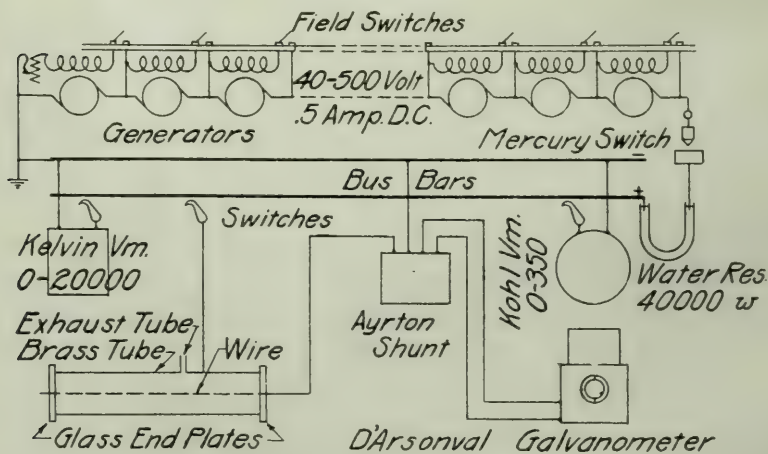


FIG. 3. DIAGRAM OF CONNECTIONS

voltage of which had previously been determined by means of a potentiometer. The voltage of the dry cell was determined both in open circuit and on closed circuit with the smallest series resistance used in the calibration placed in series with the cell. The change in terminal voltage due to the current flowing was, in every case, found to be entirely negligible.

The machines, measuring instruments, and corona apparatus were connected as is shown in Fig. 3. The arrangement of the connections made so that the corona occurs between a positive wire and a grounded coaxial cylinder will be referred to throughout this bulletin as corona with "the wire positive" or as "positive corona." Likewise, when the connections are such that the corona occurs between a positive tube and a grounded wire (as in Fig. 3), the corona will be referred to as corona with "the wire negative" or as "negative corona."

CHAPTER II

GENERAL APPEARANCE OF THE CORONA ABOUT A WIRE IN A CYLINDER

As the voltage across the corona apparatus is gradually raised, a point is reached when a marked increase in the current occurs, and a further increase in voltage causes the current to increase very rapidly. The voltage at which this sudden increase, indicated by the deflection of the galvanometer, occurs is called the "critical voltage." "Visible glow voltage" means the voltage at which the light about the wire first appears. The visible glow voltage may be identical with, or higher than, the critical voltage.

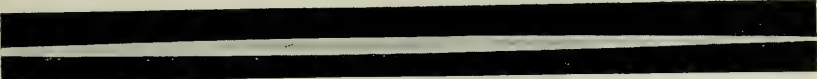
The positive and negative corona have entirely different appearances and will be considered separately.

4. *Wire Positive in Air.*—For all pressures and sizes of wire used a uniform purple glow surrounds the positive wire. The wire has a tendency to vibrate at high pressures and high current densities as is shown by *a*, Fig. 4. The thickness of the luminous film seems to be a constant for all current densities and pressures, the intensity or brilliance of the discharge only varying with the current and pressure. Positive corona in air at various pressures is shown in Fig. 4.

5. *Wire Negative in Air.*—With the wire negative the appearance of the corona is changed in a very marked degree as is shown in Figs. 4 and 5. From these photographs the following properties can be observed:

(1) With a constant wire diameter and decreasing pressures the discharge gradually changes from a fairly uniform luminous mass with ragged boundaries to a beady discharge as is shown in Fig. 5. The luminous mass is shown breaking up into beads at *f* and *g*, Fig. 4.

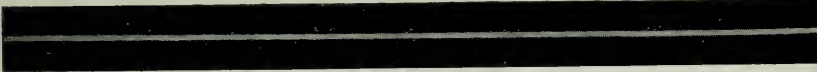
(2) For a constant pressure and decreasing wire radii the fairly uniform luminous discharge gradually changes to the beady discharge, so that for small wires (less than 0.17 mm. in diameter) the beady discharge occurs at all pressures between



(a) WIRE+, PRESSURE 747 MM., VOLTS 9110, AMPERES 11.8×10^{-5}



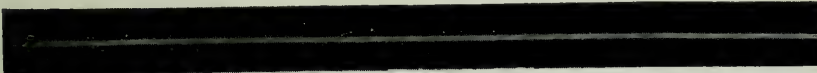
(b) WIRE-, PRESSURE 747 MM., VOLTS 8850, AMPERES 12.0×10^{-5}



(c) WIRE+, PRESSURE 427.0 MM., VOLTS 6795, AMPERES 6.60×10^{-3}



(d) WIRE-, PRESSURE 427.0 MM., VOLTS 6350, AMPERES 7.11×10^{-3}



(e) WIRE+, PRESSURE 229.0 MM., VOLTS 4680, AMPERES 6.72×10^{-3}



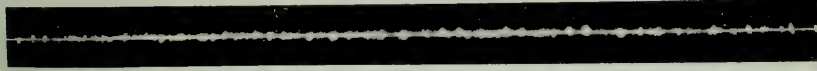
(f) WIRE-, PRESSURE 229.0 MM., VOLTS 4265, AMPERES 6.60×10^{-3}



(g) WIRE-, PRESSURE 87.0 MM., VOLTS 2200, AMPERES 6.70×10^{-3}



(h) WIRE-, PRESSURE 46.9 MM., VOLTS 1450, AMPERES 4.33×10^{-4}



(i) A. C., PRESSURE 747 MM., VOLTS 8180, AMPERES 6.65×10^{-5}

FIG. 4. VISUAL CHARACTERISTICS OF THE CORONA IN AIR



(a) WIRE—, PRESSURE 119.3 MM., VOLTS 2500, AMPERES 0.327×10^{-4}



(b) WIRE—, PRESSURE 119.3 MM., VOLTS 2800, AMPERES 1.03×10^{-4}



(c) WIRE—, PRESSURE 119.3 MM., VOLTS 3160, AMPERES 2.23×10^{-4}



(d) WIRE— PRESSURE 119.6 MM., VOLTS 3550, AMPERES 4.65×10^{-4}



(e) WIRE—, PRESSURE 119.6 MM., VOLTS 3870, AMPERES 10.0×10^{-4}



(f) WIRE—, PRESSURE 119.6 MM., VOLTS 4020, AMPERES 16.2×10^{-4}

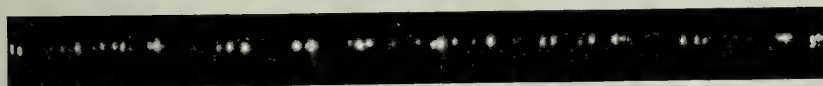
FIG. 5. VARIATION OF THE NUMBER OF BEADS WITH THE POTENTIAL DIFFERENCE



(a) WIRE—, PRESSURE 778.0 MM., VOLTS 3721, AMPERES 9.15×10^{-3}



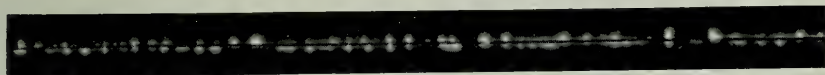
(b) WIRE+, PRESSURE 436.0 MM., VOLTS 3840, AMPERES 15.0×10^{-5}



(c) WIRE—, PRESSURE 436.0 MM., VOLTS 2390, AMPERES 18.0×10^{-3}



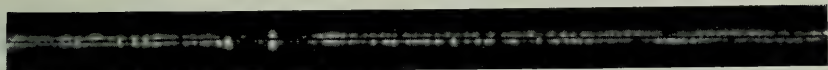
(d) A. C. PRESSURE 436.0 MM., VOLTS 2710, AMPERES 18.3×10^{-3}



(e) WIRE—, PRESSURE 391.0 MM., VOLTS 4585, AMPERES 3.57×10^{-3}



(f) WIRE+, PRESSURE 234.5 MM., VOLTS 4500, AMPERES 21.3×10^{-5}



(g) WIRE—, PRESSURE 234.5 MM., VOLTS 2025, AMPERES 1.76×10^{-3}

FIG. 6. CORONA IN HYDROGEN

atmospheric and 50 mm. of mercury. Under certain conditions of pressure and voltage these negative beads or brushes distribute themselves uniformly along the wire as is shown in Fig. 5. For the lowest pressures the beads consist of a bright cylindrical core along the wire, this core being surrounded by a narrow dark space and enveloped in turn by a purple glow of relatively large diameter. For increasing pressures the central core contracts to a point on the wire, from which the discharge spreads out fanlike in a plane at right angles to the wire. For still higher pressures the fan seems to close and finally to degenerate to a small brush.

(3) The number of brushes varies with the potential difference. That the number of brushes is a function of the potential difference is shown in Fig 5. Between the voltages at which the arrangement of the brushes was most regular, there seemed to be a transition period in which there were many little brushes in addition to those that were larger. An increase of voltage would then produce a set of full-sized brushes.

6. *Wire Positive in Hydrogen.*—With the wire positive and sizes of wire less than 0.405 mm. in diameter, the wire is surrounded by a thin luminous layer which is essentially uniform, as shown at *b*, Fig. 6. As the size of the wire is increased, this glow becomes more and more irregular. At first there are spots somewhat brighter than others. For a wire as large as 2.59 mm. the discharge takes the form of a large number of brushes similar to the point-discharge in air. It has been impossible to obtain satisfactory photographs of these brushes. They are closely spaced along the length of the wire with a fairly uniform glow between them. The positive discharge is blue in color. If the potential is increased to a high value, a brilliant red spark will pass between the wire and the tube. This spark is followed by a pale blue arc having incandescent blue spots at both ends. These arcs are illustrated in *f*, Fig. 6.

7. *Wire Negative in Hydrogen.*—The typical form of discharge with the wire negative is shown in Fig. 6. For small wires and large pressures the discharge on the wire consists of distinct bright beads with well defined edges, while for large wires and small pressures it changes to a more fuzzy discontinuous discharge. As the potential

is continually increased from values below to values above the critical point, the first evidence of a breakdown of the gas around the wires of small radii is the appearance of an intermittent flickering glow which changes almost immediately with the change of potential to a number of flickering unstable bright spots on the wire. For wires larger than 0.200 mm. in diameter the flickering glow does not form, but the beady discharge is the first to form for these wires. In all cases, however, a voltage increase causes an increase in the number of spots; the corona current gradually increases (a time element enters in the building up of the current) and finally a stage is reached where the spots condense into one brilliant bead. The formation of this bead is accompanied by an extremely rapid increase of current and a correspondingly large and rapid drop in the potential across the tube. A further increase in voltage causes more small bright spots to form, and also causes an increase in the brilliancy of the bead. The newly formed spots condense into a second bead upon a further increase in voltage, and in this manner the number of beads and the current increase as the tube voltage is increased.

If the generator voltage is now decreased, the behavior of the corona is somewhat different. If there are nine beads upon the wire, for example, they will persist but become less and less brilliant until they finally collapse into one or two beads. It seems, therefore, that with increasing voltage the beads appear one by one until the maximum voltage is reached, when the number of beads is also a maximum; but that with decreasing voltage the beads remain on the wire at much lower voltages than those at which they were formed. In fact they persist until a change in number takes place when, not only one but several beads disappear, so that the beads remaining again increase in brilliance, and a considerable lowering of the voltage is necessary to destroy more beads. With a constant number of beads the current increases with increasing voltage. The bead brilliancy increases also with an increase of current. With a change in the number of beads the current value makes a sudden change. This change is approximately proportional to the change in the number of beads.

Opposite each bead for practically all pressures and all sizes of wire used, there is a number of bright spots on the tube. The number of spots varies from ten to twelve for small wires and for small pressures to many hundred for large wires and for large pressures.

For a given wire and a given pressure the number of spots de-

pend upon the magnitude of the corona current. If only a few spots exist, they will be grouped together around the side of the bead nearest the tube, but when the current is large the spots will form a band extending entirely around the tube and of a width of one centimeter or less. These spots vary in color from pale yellow to a milky blue, depending on the pressure, current, and size of wire. With low pressures and large currents these spots may appear as brilliant green fans with yellow spots where they touch the tube. The green color may be due to the brass tube and not to an inherent property of the hydrogen. The presence of these spots at the tube surface seems to indicate an ionizing gradient in this region.

The predominating color of the various discharges through hydrogen is blue, which ranges from a light silver blue to sky blue. The exceptions to this characteristic blue color have been mentioned in the preceding paragraph.

8. *Alternating Current Corona in Air and Hydrogen.*—When an alternating voltage is impressed across a tube filled with air, the discharge seems to be a combination of the discharges with the wire positive and with the wire negative. As would be expected, the beads appear during the half cycle when the wire is negative and the uniform glow appears during the half cycle when the wire is positive. This is shown in *i*, Fig. 4.

When alternating current is applied to a tube filled with hydrogen, the discharge always appears to be very similar to that observed when the wire is negative, as shown clearly in *d*, Fig. 6. The absence of the uniform luminous layer between the beads shows that the characteristic positive discharge is absent; thus either partial or perfect rectification is indicated. The absence of the positive discharge can better be understood after studying the starting points of the positive and negative corona, as shown in the curves which follow.

If the alternating voltage is sufficiently increased the positive corona discharge forms, and finally with a sufficient increase the positive arc is produced. That the arc occurs during the half cycle in which the wire is positive can be verified by two methods. (1) By watching the discharge as the voltage is increased to the arcing value, one observes the first arc to be a reddish color. This is known to be the positive arc. (2) Oscillograms show that the change in current, indicating the start of the arc, occurs from a positive current lobe.

CHAPTER III

THE STARTING POINT OF THE CORONA

For engineering purposes it is important to know the factors which affect the starting point of the visible glow. In air, of a given humidity, the starting point* is mainly a function of two variables: (1) the radius of the wire, (2) the pressure of the air. In hydrogen the first few investigations disclosed the fact that the starting voltages were erratic under apparently similar temperature, pressure, and wire surface conditions. All disturbing elements, except possibly a time element, seemed to be eliminated; so tests were made to determine the effect on the starting voltage of a variation in the length of time elapsing between successive readings. Fig. 7 shows the results of a repre-

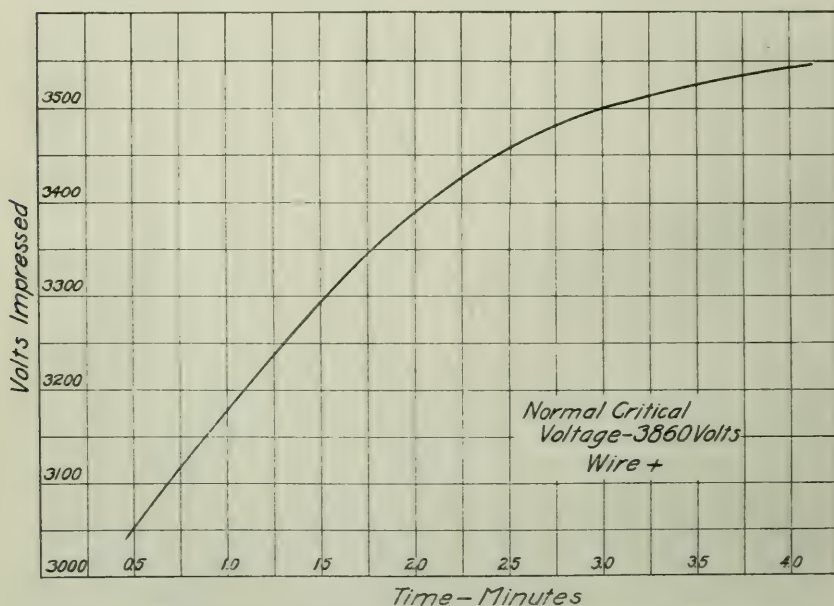


FIG. 7. VARIATION OF CRITICAL VOLTAGE WITH TIME INTERVAL BETWEEN OPENING AND RECLOSING THE CIRCUIT

*The influence of humidity and temperature upon the starting point will be discussed in Chapter V.

sentative test of this type. The method of procedure for taking the readings for this test was as follows: The circuit was closed, corona was started, and the voltage was increased to a value sufficient to make the current reading 2.472×10^{-4} amperes. The circuit was then opened, and the time of opening the circuit was called zero time. One-half minute later the circuit was closed and the critical voltage value was determined as soon as possible. After this determination was made, the current was again brought to 2.472×10^{-4} amperes, the circuit opened and the new time was called zero time. A critical voltage determination was made one minute later. This process was continued until a definite conclusion concerning the variation of critical voltage with time was reached. As a direct consequence of this test all determinations of critical voltages in hydrogen were made only when enough time had elapsed after breaking the corona circuit to insure a resumption of normal conditions.

Experiments were also conducted to determine whether or not the starting voltage was different for the two following cases: (1) when the voltage was gradually increased in value until the critical value was reached, and (2) when the full voltage was suddenly thrown across the tube. No appreciable difference was found.

In addition to this time element the starting point of the visible glow in hydrogen also depends upon the radius of the wire and the pressure of the gas. In the next two sections the variations of the glow voltage with these factors are discussed.

9. *Glow Volts—Radius Curves.*—Fig. 8 gives curves showing the variation of the glow voltages with the radius of the wire when air and hydrogen formed the dielectric. In the air curves the data for points representing wires of very small radii were taken from voltage-ampere curves for silver and tungsten wires. The data for the rest of the points were taken from the characteristic voltage-ampere curves for copper as reproduced in this bulletin. The silver wire used was really silver wire with a platinum core, known as "Wollaston wire." It was used both in its original state, diameter 0.0517 mm., and with some of the silver dissolved off; thus the wires used were of average diameters 0.027 and 0.037 mm. The tungsten wire was that used in 25-watt lamps. The diameters of the very small wires were obtained by the use of a microscope fitted with a stage ruled with parallel lines.

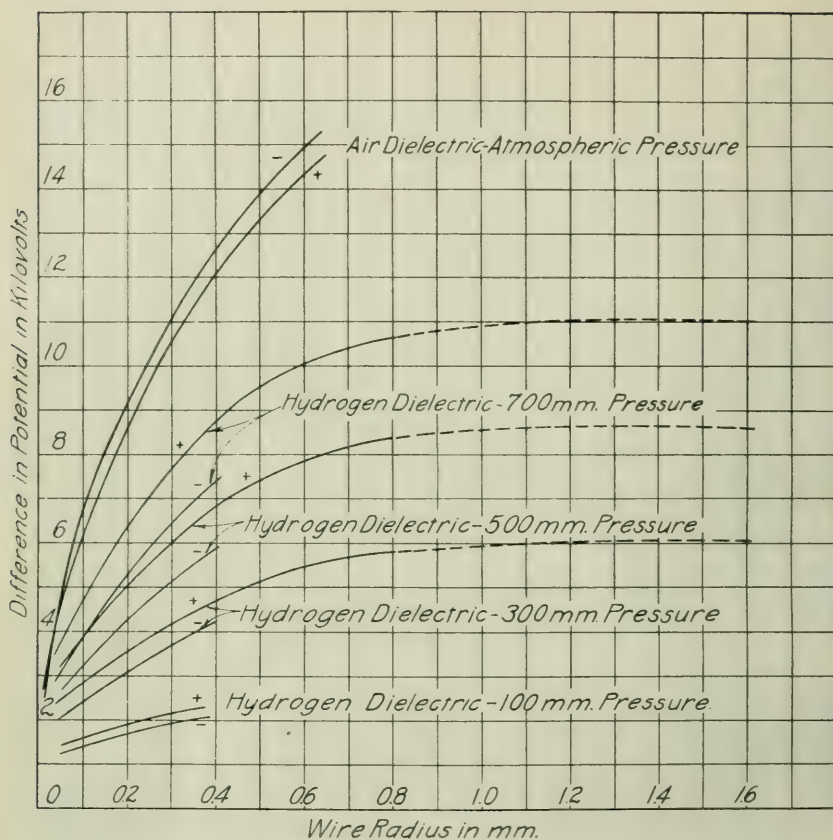


FIG. 8. VARIATION OF THE GLOW VOLTAGES WITH THE RADIUS OF THE WIRE

From the air curves the following conclusions can be drawn:

(1) For the smaller wires, the negative glow appears before the positive.

(2) For the larger wires, the positive glow appears before the negative.

(3) The diameter of wire, 0.075 mm., serves as a dividing line between these two groups. Shaffers has noted similar data which when plotted show a crossing of the curves for the starting points of the positive and negative corona, but he gives 0.01 cm. as the wire radius to separate the two groups. He does

not specify what he considered as the starting point of the negative corona, and it is accordingly not practical to compare his value with that shown in the air curves.

The hydrogen curves show: (1) that the critical voltage for hydrogen is very much less than that for air, (2) that for any particular size of wire and any given pressure the negative starting voltage is much less than the positive voltage. It is seen that for most of the range of wires used the opposite is true for air.

10. *Glow Volts—Pressure Curves.*—Fig. 9 gives curves showing the variation of critical voltages with the pressure. In these experiments only one wire was used when the tube was filled with air but each of two wires was successively used when the tube was filled with hydrogen.

These curves show that in both air and hydrogen for a single size of wire, an increase in the gas pressure requires an increase in the voltage necessary to start the corona discharge. These curves also

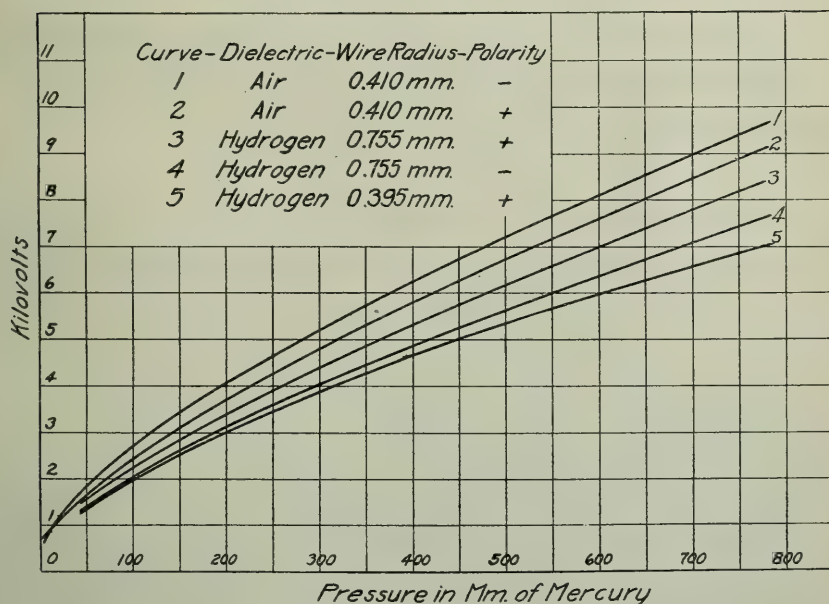


FIG. 9. VARIATION OF THE GLOW VOLTAGES WITH THE GAS PRESSURE

show: (1) that the positive critical voltage for air is lower than the negative critical voltage, while for hydrogen the negative critical voltage is the less; (2) that for a constant pressure and size of wire the critical voltage in hydrogen is much lower than the critical voltage in air.

11. *Starting Point Expressed in Terms of Electric Intensity as a Function of Radius and Pressure.*—The electric intensity, ϵ , at the surface of the wire, subject to a potential, V , coaxial with a cylinder at zero potential, is given by the following equation:

$$\epsilon = \frac{V}{a \log_e \frac{b}{a}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where a = radius of the wire,

b = radius of the cylinder.

Thus if V , a , and b are known, ϵ can be computed. A sample table showing glow voltage and computed electric intensity as a function of the radius of the wire in air is given in Table 1. While with increasing radius the glow voltage increases, the electric intensity, ϵ , at the surface of the wire decreases. Fig. 10 shows this relation graphically.

TABLE 1

CRITICAL DIFFERENCE OF POTENTIAL TO CAUSE CONTINUOUS GLOW AS
FUNCTION OF RADIUS OF WIRE

1 R cm.	2 V+Volts	3 E+Volts per cm.	4 E+Volts Calcul.	5 V-Volts	6 E-Volts per cm.	7 E-Volts Calcul.
0.00135	2720	2.74×10^5	2.62×10^5	2520	2.52×10^5	2.55×10^5
0.002185	3380	2.58	2.29	3230	2.45	2.23
0.0023	3500	2.25	2.09	3300	2.08	2.04
0.00258	3630	2.12	1.99	3500	2.02	1.94
0.00386	4060	1.66	1.67	4060	1.66	1.65
0.00678	5140	1.31	1.34	5320	1.36	1.33
0.00825	5710	1.25	1.25	6140	1.21	1.21
0.012	6600	1.07	1.09	6840	1.09	1.09
0.013	7180	1.07	1.06	7660	1.14	1.06
0.0205	8900	0.93	0.91	9370	0.99	0.92
0.0325	10880	0.80	0.79	11440	0.83	0.80
0.0385	11850	0.77	0.75	12400	0.79	0.76
0.0512	13500	0.71	0.69	14120	0.73	0.71
0.0642	14700	0.65	0.65	15220	0.64	0.64

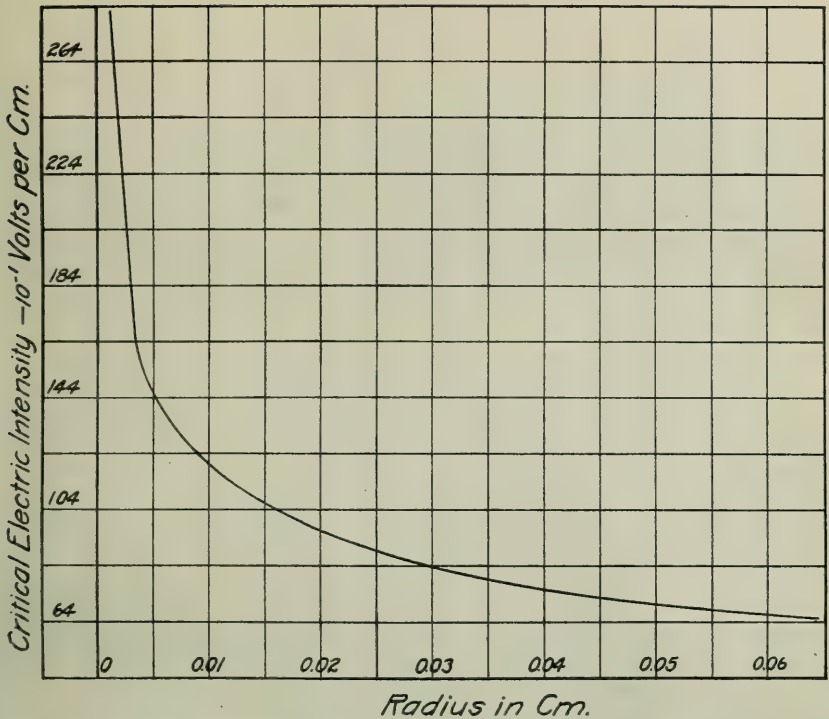


FIG. 10. CRITICAL ELECTRIC INTENSITY AT THE SURFACE OF THE WIRE AS A FUNCTION OF THE WIRE RADIUS

Peek has found that the following law, connecting electric intensity and radius, holds:

$$\epsilon = A + \frac{B}{\sqrt{a}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where A and B are constants and a is the radius of the wire. The data in columns 3 and 6 of Table 1 were obtained by substitution in equation (1) and columns 4 and 7 by substitution in the empirical law represented by equation (2). By comparing columns 3 and 4, and 6 and 7, one sees that for the smallest wires there are deviations from this formula. These deviations occur probably because the critical voltage and the glow voltage differ from each other, and because there is possibly a distortion of the field due to ionization before the glow begins. For the data given it is found that for the positive

wire $A = 31.6 \times 10^3$, $B = 8.47 \times 10^3$; and for the negative wire $A = 35.0 \times 10^3$, $B = 8.06 \times 10^3$.

In hydrogen the relation between electric intensity and the wire radius follows equation (2) only approximately, and then only for wires whose radii fall within the limits from 0.1 mm. to 1.0 mm., and for gas pressures ranging from 100 mm. of mercury to atmospheric pressure. For wires of diameters larger than 1.0 mm., the ratio of the radius of the wire to the radius of the tube becomes comparatively small and the discharge phenomena change their character until with a No. 8 wire, 3.23 mm. in diameter, corona does not form at any pressure.

From the curves showing the relation between the critical voltage and the pressure, found by computing the electric intensity, curves could be drawn showing the relation between electric intensity and pressure.

Such curves taken from data with hydrogen can be represented nearly accurately by another one of Peek's formulas.

$$\epsilon = \epsilon_0 p + c \sqrt{p} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where ϵ = critical electric intensity at wire,

p = pressure in percentage of atmospheric pressure,

ϵ_0 and c = constants.

These two laws of Peek can be combined into the one equation:

$$\epsilon = \epsilon_0 p \left(1 + \frac{D}{\sqrt{ap}} \right) \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where ϵ_0 and D are constants, and a and p have the significance given to them. For both air and hydrogen it has been found that this law represents the facts only very approximately, especially is this statement true for large wires and low gas pressures. In hydrogen the critical and glow voltages have identical values for all sizes of wire and pressures studied.

12. *Theoretical Considerations.*—Several attempts have been made to give theoretical explanations of the corona discharge. No theory, however, has succeeded in explaining all the phenomena. In many cases the theory of spark discharge has been applied to the corona. Spark and corona are, however, different phenomena. In

the spark there is no distinction between positive and negative; whereas this distinction in the corona is very necessary. In order to start a spark a high potential difference, as a rule, is required; but as soon as the spark strikes, the potential difference falls to a very small value. This is not the case for the corona in air; moreover when the corona is started one has to raise the potential difference a great deal before a spark or rather an arc appears completely across the gas between the electrodes. In the case of the spark the striking potential difference, V , depends only on the pressure, p , of the gas and the distance, d , between the electrodes:

$$V = C p d$$

where C is a proportionality factor. This law is found by the following consideration. Suppose that there are a few electrons present in the gas in the natural state. If an electric force, $\epsilon = \frac{V}{d}$, is applied, and if λ is the average distance between successive collisions of an electron with a molecule, then this distance, λ , must be such that the force, ϵ , has time enough to impart to the electron the energy, E_c , required to ionize the molecule; hence

$$\epsilon = \frac{E_c}{\lambda} = \frac{V}{d}, \text{ or } V = \frac{E_c}{\lambda} d;$$

but λ , the distance between ionizing collisions, is inversely proportional to the pressure of the gas; hence $V = C \cdot d \cdot p$, or the striking potential difference, V , is constant if $p \cdot d$ is constant. The spark depends only on the properties of the gas, especially on the mass of the gas between the two electrodes, but it is independent of the electrodes.

The apparent law of the corona discharge is quite different. The electric force, ϵ , which must be applied in order to start the corona discharge depends not only on the pressure of the gas but also on the radius of the wire approximately according to the expression

$$\epsilon = \epsilon_0 p \left(1 + \frac{D}{\sqrt{R_r}} \right)$$

or for constant pressure: $\epsilon = A + \frac{B}{\sqrt{R}}$

For small wires a relatively strong electric force is required. A later chapter will show that not only the radius of the central wire but also

its mechanical and chemical properties affect the initial discharge. At all events in the negative corona it seems as if the electrons were supplied in part by the metal and not only by the gas.

A partial explanation of the last formula can be given as follows: assume that in the neighborhood of the wire in a layer of constant thickness, δ , a certain constant energy is required for the beginning corona, different for positive and negative electricity; in fact the splitting up of the molecules into ions and the emission of light require energy. When a sufficient amount of energy is supplied, the breaking down of the dielectric accompanied by the luminous corona will occur. The thickness, δ , of the luminous layer seems nearly independent of the radius of the wire. In the neighborhood of the wire, the electric force, ϵ , assumes large values so that the polarization is also large and an opposing electric force, ϵ_0 , of polarization will be created, so that the resultant electric force is equal to $\epsilon - \epsilon_0$. If k is the dielectric constant, R_1 , the radius of the wire, then the energy, E_1 , per unit length in a layer of thickness, δ , around the wire is:

$$E_1 = \frac{k}{8\pi} 2\pi R_1 \delta (\epsilon - \epsilon_0)^2$$

$$\epsilon = \epsilon_0 + \sqrt{\frac{4 E_1}{k R_1 \delta}}$$

If E_1 , k , and δ are constant, then

$$\epsilon = \epsilon_0 + \sqrt{\frac{4 E_1}{k \delta}} \frac{1}{\sqrt{R_1}}, \quad \text{the law which approximately}$$

represents these observations.

The principle of similarity is now applied to two tubes, T and T'_1 , where the linear dimensions are in the constant ratio of $1:z$, so that

$$R'_1 = R_1 z; \quad R'_2 = R_2 z; \quad \text{then } \epsilon_1 = \frac{V}{R_1 \log \frac{R_2}{R_1}}$$

$$\epsilon'_1 = \frac{V}{R'_1 \log \frac{R'_2}{R'_1}} = \frac{V}{R_1 z \log \frac{R_2}{R_1}} = \frac{\epsilon_1}{z}, \quad \text{provided the potential dif-}$$

ference, V , is the same in both tubes. The discharge will start under the same potential difference if $p' = \frac{p}{z}$; then for the mean free paths in both tubes the relation is: $\lambda' = \lambda z$ and for the time intervals, t' and t respectively, between two successive collisions: $t' = t z$. At any two corresponding points such as A and A' the electric forces are:

$$\epsilon = \frac{e}{r^2}, \quad \epsilon' = \frac{ez}{r^2 z^2} = \frac{\epsilon}{z},$$

because it is assumed that at any moment the distribution and movement of the ions in the tubes are exactly similar, but that the total numbers are in the ratio of $1:z$; hence

$$\epsilon' \lambda' = \frac{\epsilon}{z} \lambda z = \epsilon \lambda$$

$\epsilon \lambda$ is, however, the work done by the electric field during the motion of an ion over a mean free path; if after this mean free

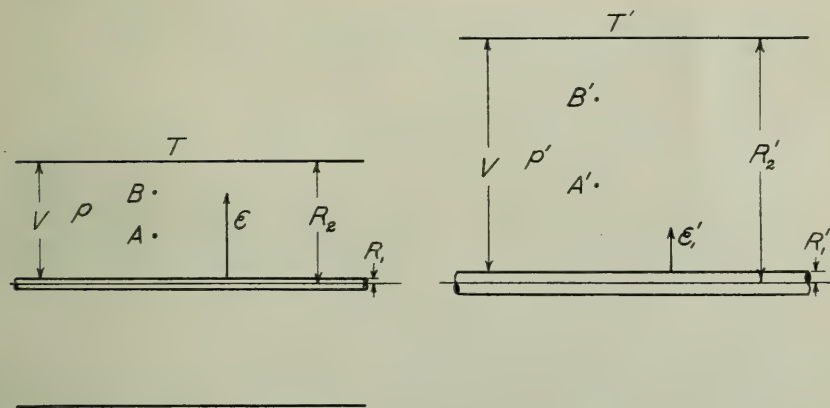


FIG. 11. THEORETICAL TUBES WITH LINEAR DIMENSIONS IN CONSTANT RATIO

path the next collision results in ionization, it will do so in corresponding points of both tubes. Moreover

$$\epsilon'_1 R'_1 = \frac{\epsilon_1}{z} R_1 z = \epsilon_1 R_1 \text{ and}$$

$$p' R'_1 = \frac{p}{z} R_1 z = p R_1; \text{ hence}$$

if $\epsilon_1 R_1$ is kept constant, then $p R_1$ remains constant; or $\epsilon_1 R_1$ is

only a function of $p R_1$. If $\epsilon_1 = \epsilon_0 + \frac{b}{\sqrt{R_1}}$, then

$$\epsilon_1 R_1 = \epsilon_0 R_1 + \frac{b R_1}{\sqrt{R_1}}, \text{ for } p = 1.$$

But if $R_1 + 1$ is kept constant and is equal to $R_1 p$, then $\epsilon_1 R_1$ remains constant; hence

$$\epsilon_1 R_1 = \epsilon_0 R_1 p + \frac{b R_1 p}{\sqrt{R_1 p}}, \text{ or}$$

$$\epsilon_1 = \epsilon_0 p + \frac{b p}{\sqrt{R_1 p}}, \text{ or}$$

$$\epsilon_1 = p \left(\epsilon_0 + \frac{b}{\sqrt{R_1 p}} \right),$$

a rule approximately verified at least by experimental measurements in air.

CHAPTER IV

CHARACTERISTIC CURVES

A characteristic curve for the corona discharge shows graphically the relation between the voltage across the tube and the resultant current. Such curves will be considered in the following paragraphs for air and hydrogen at various pressures.

13. *Ampere-Voltage Characteristic Curves for Air at Atmospheric Pressure.*—It was found that the currents flowing, when the voltages were below the critical voltage, were negligible; consequently the following tests were started at a voltage somewhere near the critical voltage. For each voltage the deflection of the galvanometer was read for both polarities of the wire.

The presence of dirt or dust particles on the wire, when negative, has a marked effect upon the discharge. Often a spot or two on the wire would glow long before the wire as a whole was luminous. Because of this fact there is no definite critical voltage as in the positive polarity, for the initial jump of the deflection is much a matter of chance. As the voltage is increased, however, there occurs a critical voltage at which a flickering glow can be seen along the wire preliminary to the spreading of the discharge from a few spots over the whole wire. This phenomenon occurs at a definite voltage for a given size wire and it is this voltage which is given in the tables under "visible glow" for the negative polarity.

Fig. 12 shows the characteristic curves and critical voltage for copper wires of diameters ranging from 0.41 mm. to 1.28 mm.

A study of these data shows the following facts:

(1) For the smaller wires, the critical voltage is considerably lower than the glow voltage, and a fairly large current exists before a luminous discharge occurs. This statement applies to wire positive.

(2) The smallest wire, for which there is no current for wire positive before glow appears, is 0.135 mm. diameter.

(3) For wires larger than 0.135 mm. diameter, current and glow appear simultaneously, for wire positive.

(4) For wires about No. 26 and larger the current and the visible glow appear simultaneously, as a general rule, for the negative polarity.

14. *Characteristic Curves in Air at Reduced Pressures.*—It was discovered that a change in the pressure of the air in the corona apparatus had a marked effect upon the current caused by a given voltage; thus it was determined to obtain characteristic curves at reduced pressures for different wires. From such data it was hoped that the current readings for the different sizes of wire might be reduced to a 760 mm. basis. A series of characteristic curves was, therefore, taken for different pressures with dry air in the tube. Fig. 13 shows these results for No. 26 copper wire. These curves show a marked increase in the current for a relatively small decrease in

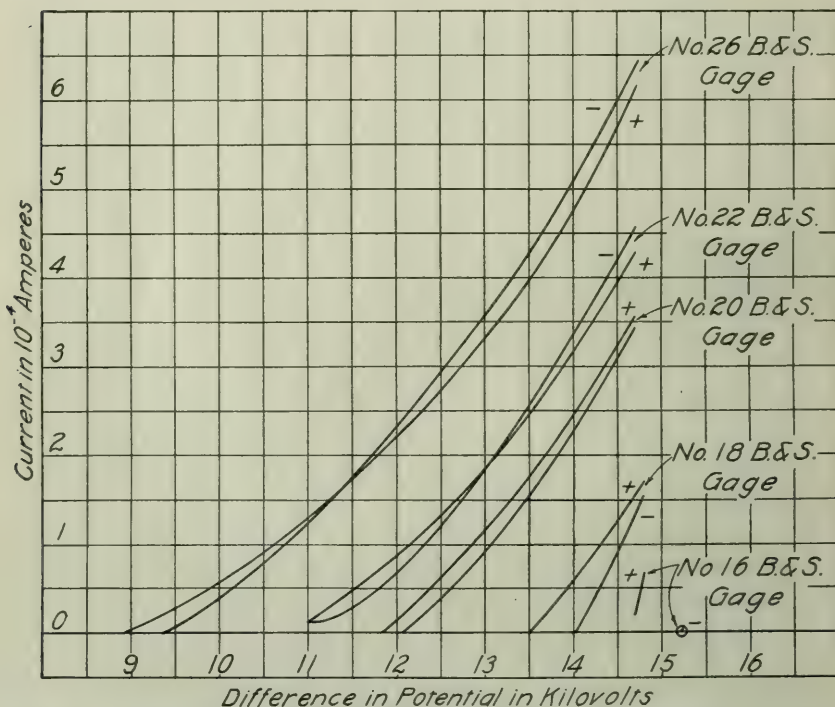


FIG. 12. CHARACTERISTIC CURVES FOR THE CORONA DISCHARGE WITH VARIOUS WIRE DIAMETERS

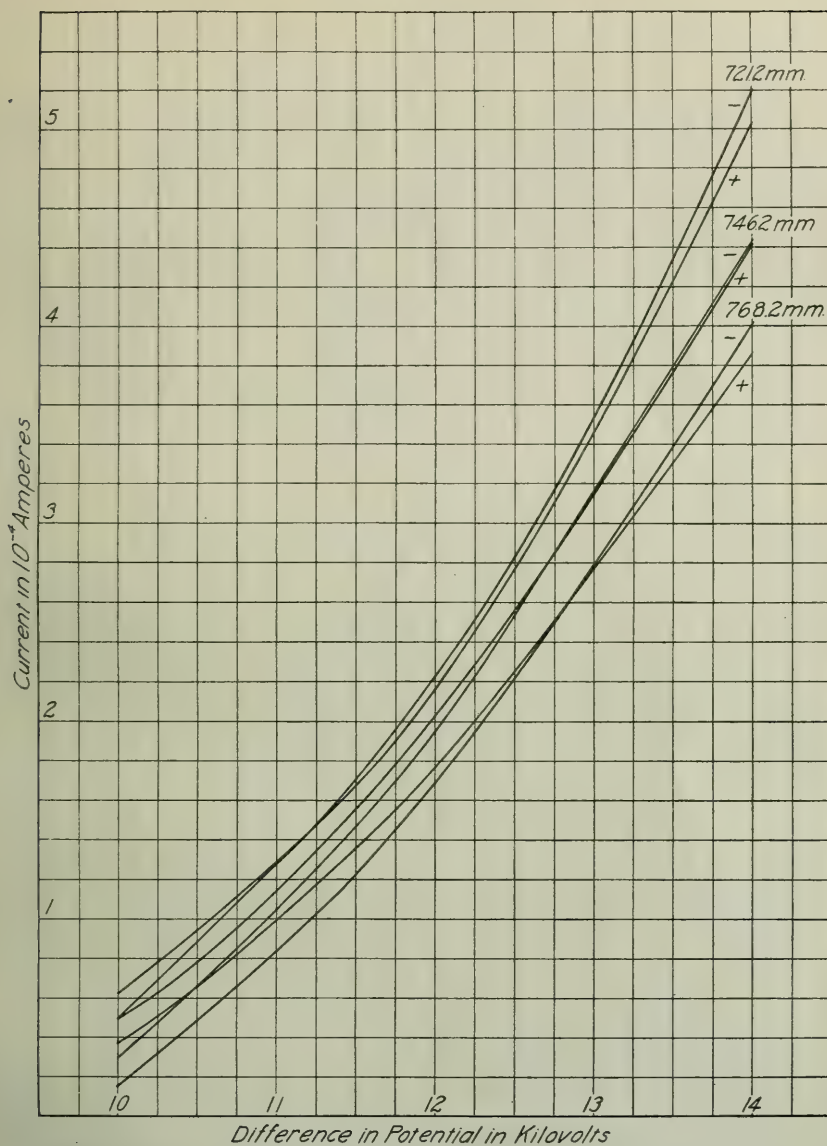


FIG. 13. CHARACTERISTIC CURVES FOR NO. 26 B. AND S. GAGE COPPER WIRE WITH AIR UNDER VARIOUS PRESSURES

the pressure. The curves also show an unsymmetrical spacing which suggests the presence of some disturbing factor.

In a number of preliminary experiments it was found to be impossible to repeat observations if the tube was closed and the air not changed. In order to eliminate any disturbing effects due to moisture in the air and possible changes in the constitution of the air in the tube, an arrangement was devised for supplying dry air which could be pumped through the tube out into the atmosphere. The air was dried by being passed through wash bottles containing sulphuric acid and then through a tube containing soda-lime. Fig. 14 shows the results when No. 40 wire was used. These curves show a regular effect of pressure which is larger for the negative than for the positive corona. This regularity seems to indicate that the discordant results

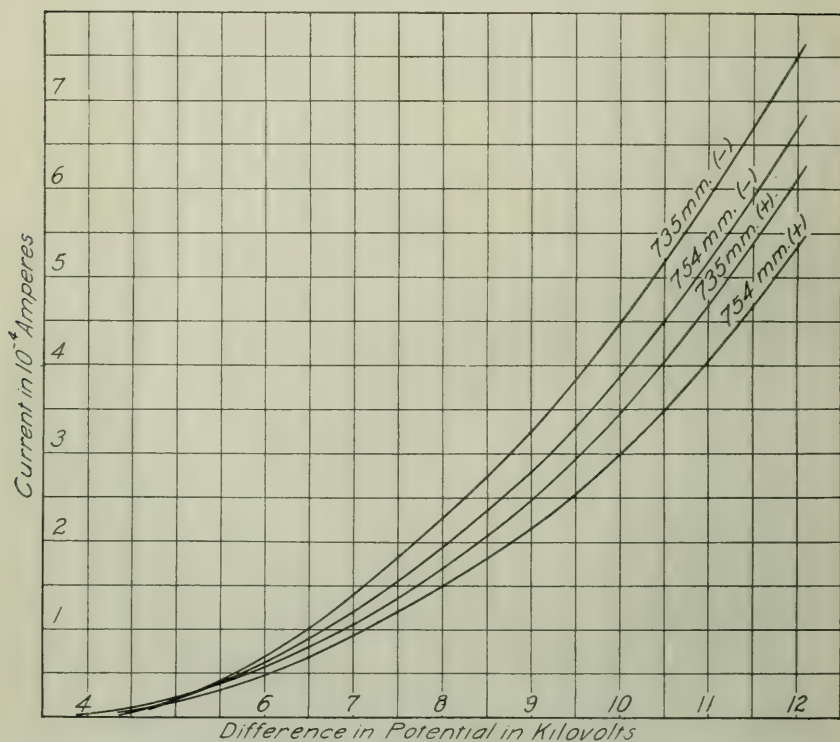


FIG. 14. CHARACTERISTIC CURVES FOR NO. 40 B. AND S. GAGE COPPER WIRE WITH DRY AIR UNDER VARIOUS PRESSURES

obtained in the preliminary experiments were due to the presence of other factors rather than mere change of the pressure.

To determine the effect, if any, of confining air in a closed tube upon the coronal current a series of tests was run under constant pressure with various conditions as, for examples, the closing of the tube, the renewal of the air. The erratic results which followed showed no evident relations and indicated that confinement of the air has a great effect upon the coronal current and also upon the critical and visible glow voltages. Such an effect does not appear strange when one thinks of the ozone, and possibly other products formed which, when the tube is closed, must remain inside and thus change the character of the gas to a considerable extent. It must be concluded from these tests that it is unsafe to compare results obtained in a closed tube with those obtained where there is a plentiful supply of fresh air.

15. *Characteristic Curves in Hydrogen at Atmospheric and Reduced Pressures.*—Some characteristic curves for positive corona in hydrogen are given in Figs. 15 and 16. The most remarkable points about these characteristics are:

(1) The marked difference between the critical voltage and the voltage at which corona ceases.

(2) The difference between the points taken with increasing and those taken with decreasing current.

This persistence of corona at voltages less than that necessary to start the discharge has not been observed with air and continuous potentials.* If there is any such difference for air, its magnitude is certainly very much less than with hydrogen.

This difference between the critical voltage and the voltage at which corona is maintained may be explained by the change in the electric intensity (volts per centimeter) at the surface of the wire after the corona has formed. This change of intensity is caused by the space charge due to the positive and negative ions in the space between the wire and the tube. That such a distortion of the electric field exists will be shown later. The difference between the critical

*See Bennett, A. I. E. E., Proc. Vol. 32, Part II, p. 1796, 1913, for alternating potentials.

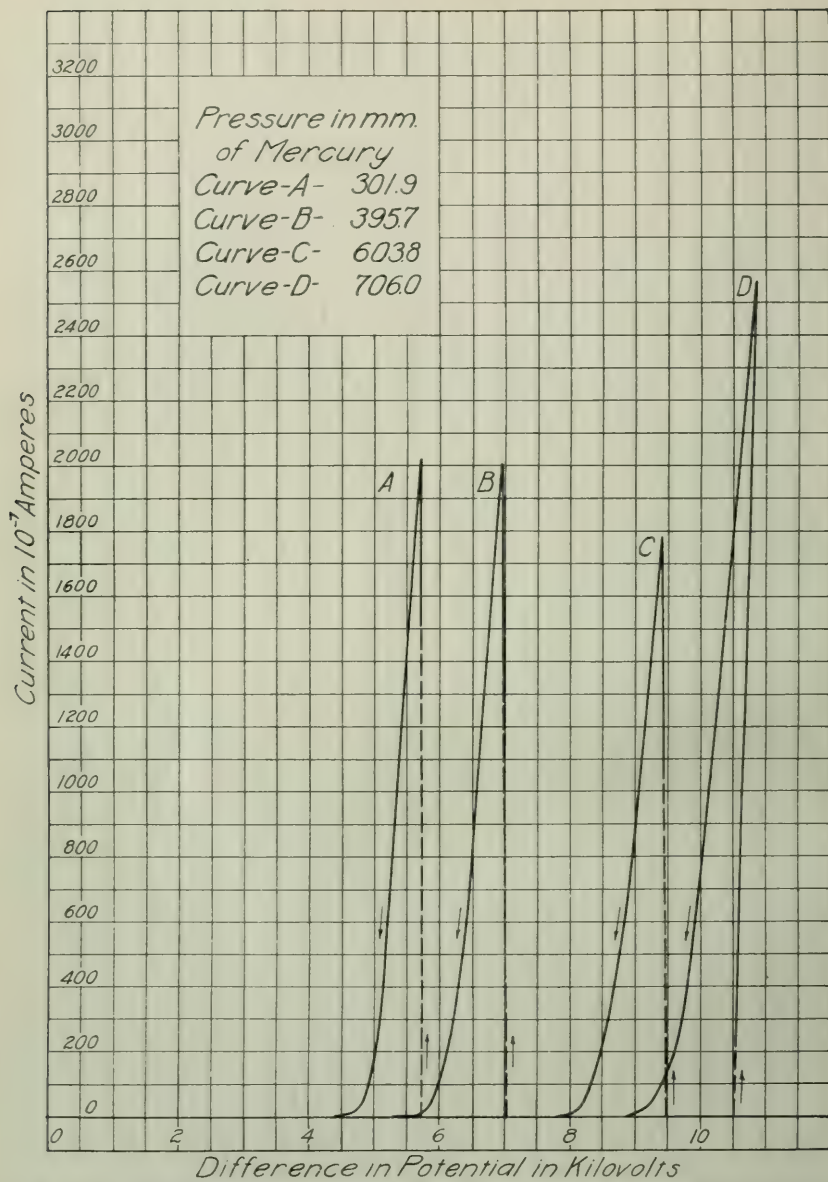


FIG. 15. CHARACTERISTIC CURVES FOR NO. 14 B. AND S. GAGE COPPER WIRE IN HYDROGEN FOR VARIOUS PRESSURES, WIRE +

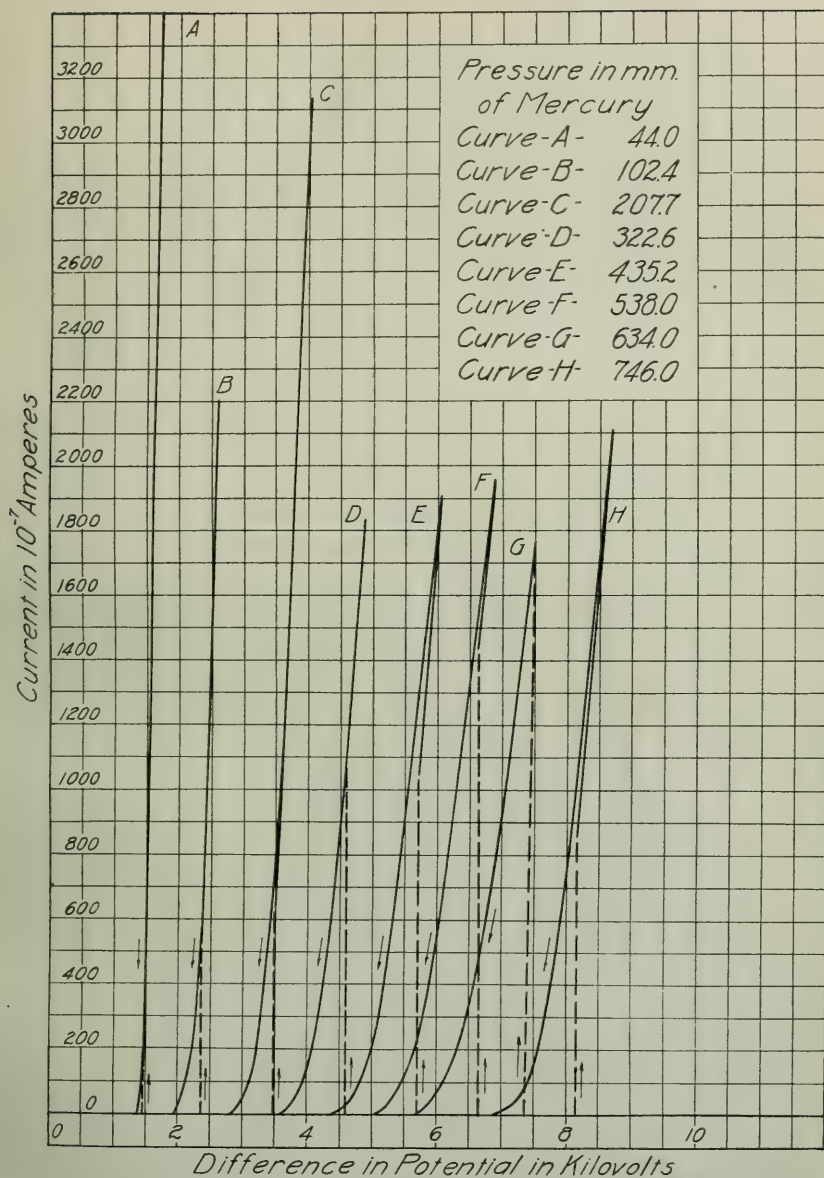


FIG. 16. CHARACTERISTIC CURVES FOR No. 20 B. AND S. GAGE COPPER WIRE
IN HYDROGEN FOR VARIOUS PRESSURES, WIRE +

voltage and the voltage at which the discharge ceases is not detected unless all sources of irregular ionization, such as rough spots on the wire, high intensity where the wire passes through the glass, etc., are eliminated.

Other properties of the characteristic curves are:

(3) For a given voltage the current increases with a decrease of density of hydrogen.

(4) For a given voltage the current increases with a decrease in wire diameter.

(5) The characteristic curve is very nearly parallel with the current axis so that a small change in potential produces a very great change in current.

(6) As soon as the copious ionization stage is reached, the current rises to a high value. For wires as large as No. 8 the current increases immediately to arcing values. As the size of the wire is decreased the initial jump diminishes until with a No. 32 wire (0.200 mm. in diameter) at atmospheric pressure the current rises to a value of the order of 10^{-4} amperes.

(7) With a single size of wire and varying pressures, the initial current rise diminishes with a decrease in pressure.

Characteristic curves for negative corona for various pressures and two sizes of wire are given in Figs. 17 and 18. The full line curves represent stable conditions and a constant number of beads. The number of beads on any particular curve may be determined by noting the small number adjacent to the curve. In the small wire it will be noticed that the shape of these characteristics depends to a large extent upon the gas pressure.

With the smaller wire (No. 36 diameter .0121 mm.) the corona seemed to start in each case with a number of very small bright points on the wire. Usually, however, the negative corona started with an unstable flickering glow along the wire. With an increase of voltage the current gradually increased until a point was reached where the small bright spots combined into one negative bead of the kind described in Chapter II. This change in formation was accompanied by a large increase in current and by a drop in the potential difference between the wire and the tube. This drop in potential difference across the tube was, in a certain sense, due to the resistance

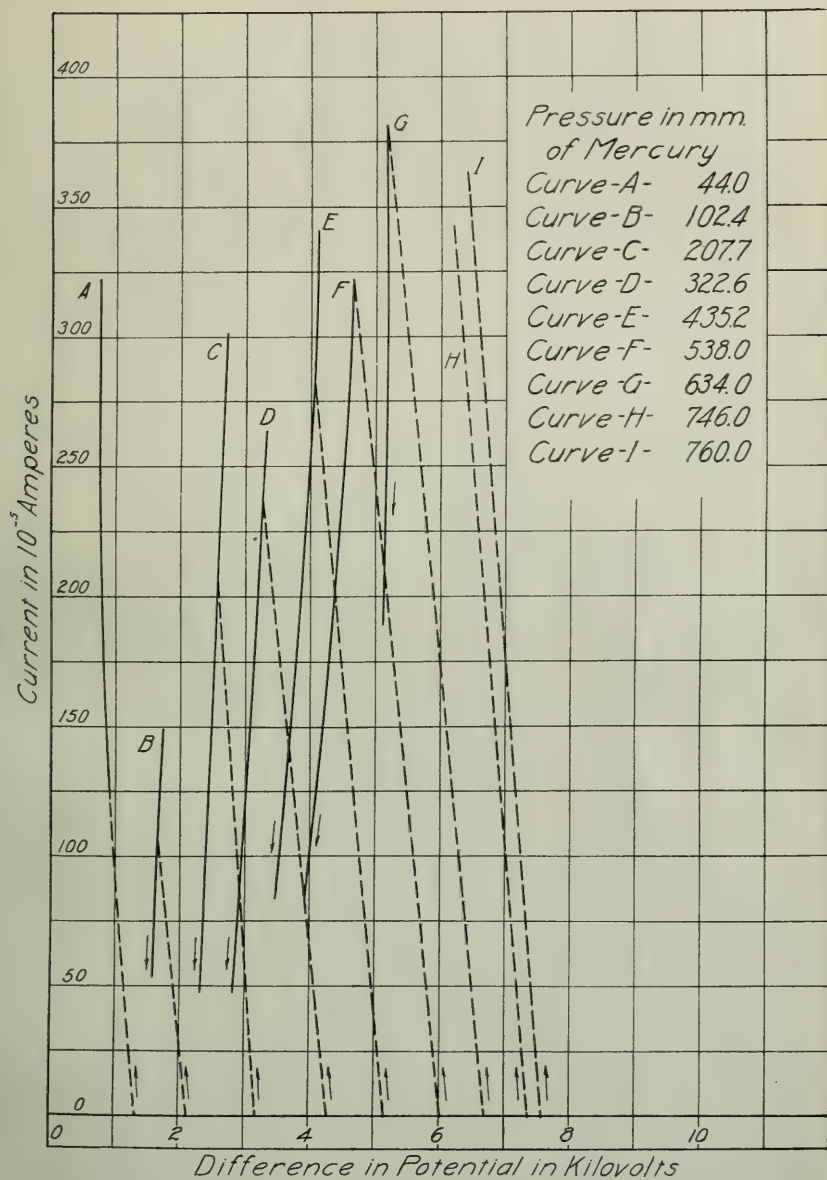


FIG. 17. CHARACTERISTIC CURVES FOR No. 20 B. AND S. GAGE COPPER WIRE IN HYDROGEN FOR VARIOUS PRESSURES, WIRE -

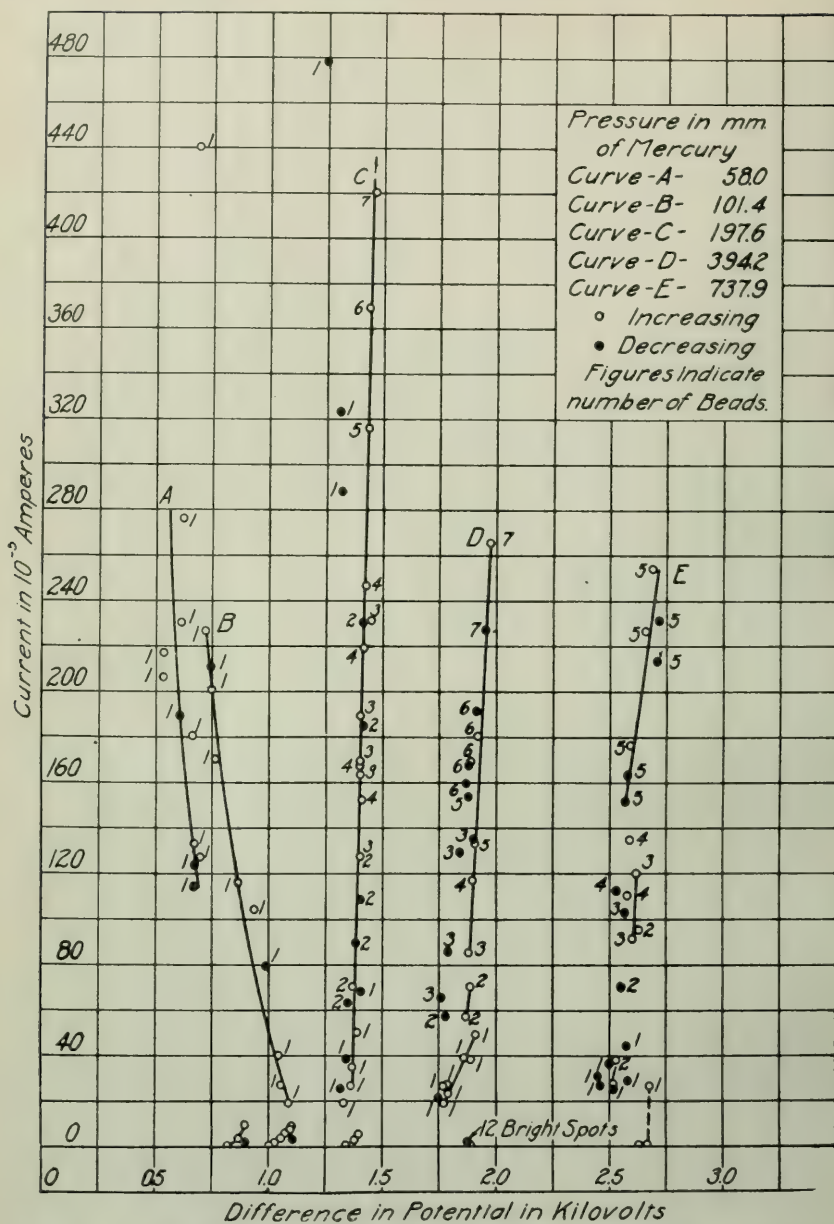


FIG. 18. CHARACTERISTIC CURVES FOR NO. 36 B. AND S. GAGE COPPER WIRE IN HYDROGEN FOR VARIOUS PRESSURES, WIRE -

in series with the corona tube. The increased current taken by the tube causes a higher drop through the series resistance. This increased drop stabilizes the corona discharge and prevents the indefinite increase of current which might result if there were no resistance in the circuit. The gaps in the curves represent unstable conditions. An increase in the generated voltage caused an increase in the corona current, which was accompanied by either an increase or a decrease of the voltage between the wire and the tube depending on the size of wire and the gas pressure.

It may be noticed that for the lower pressures the characteristics are similar to the usual arc characteristic. The discharge, however, was not that of the arc. The arc formed if the machine voltage was sufficiently increased. This increase was accompanied by a further drop in the voltage between the wire and tube and an entire change in the general appearance of the discharge.

The study of the negative characteristics leads to the following conclusions:

(1) For larger wires the curves for a constant number of beads have positive slopes at all pressures above 100 mm.

(2) For a given wire and gas pressure the curves become more nearly parallel with the current axis as the current increases in value.

(3) For a given number of beads and a constant pressure the maximum possible voltage variation is approximately a constant, whatever the number of beads.

(4) With a constant radius and a decreasing pressure the curves revolve in a counter-clockwise direction about their lower points until their slopes change from positive to negative values. The discharges become unstable at the point of infinite slope and resemble the arc discharge in so far as this property is concerned.

(5) With a constant pressure and decreasing radius the critical electrical intensity decreases, and the slopes of the curves approach negative values.

(6) In all cases, as the voltage is gradually increased through the critical value, the beads form one by one, the current values at any time being approximately proportional to the num-

ber of beads. The initial current values never became excessive as they do with the positive corona discharges.

(7) For a given voltage the current increases with a decrease of gas density and also for a decrease of wire radius.

(8) The greater the number of beads on the wire the greater the current change per unit change of potential.

(9) For all but the smallest wire studied the first corona discharge takes the form of beads. For the smallest wire the first discharge at pressures below 200 mm. of mercury takes the form of a flickering unstable glow traveling along the wire. This glow condenses to small, flickering, and unstable beads upon a slight potential increase. These flickering beads persist until currents of the order of 10^{-4} amperes are obtained; then they condense to the ordinary bead discharge.

CHAPTER V

ADDITIONAL FACTORS AFFECTING THE STARTING POINT AND THE
CORONA CURRENT

The characteristic and starting point curves show the effect upon the corona current of varying the radius of the wire and the pressure of the gas. In addition to these the following variables also affect the current.

16. *Moisture*.—The effect of moisture has been studied only when air was the dielectric. An arrangement was devised whereby air could be drawn from the room through the tube. The humidity of such air was given by calculation from the readings of wet and dry bulb thermometers. Parallel sets of readings of the current flowing when dry air was pumped continuously through the tube and when air from the room was sucked through before each reading were taken from day to day. The results are shown in Fig. 19. These curves indicate a regular effect due to moisture, with a tendency for the decrease of current by humidity to be greater for negative polarity of the wire. The decrease of current by the presence of moisture is well known; so these results agree with present knowledge.

To determine whether the presence of moisture in the air has an effect upon the critical voltage, a test was run as follows under a pressure of 736 mm. and humidity 68.5 per cent. Air was drawn from the room through the tube, and the voltage was noted at which the initial jump of the galvanometer occurred for wire positive. The positive glow voltage and the negative glow voltage were then determined. Then dry air was pumped through the tube and the same measurements were taken. The results were:

	Wet Air	Dry Air
Positive critical voltage	4300	4190
Positive glow voltage	4350	4260
Negative glow voltage	4275	4370

The effect of moisture apparently is to raise slightly the starting

point of the positive corona, but the reverse is true for the negative polarity.

The appearance of the discharge is also affected by moisture, when the wire is negative. With moist air in the tube, the discharge begins with dim spots, and the discharge is of no clearly defined nature, being a mixture of sections of continuous glow and bright spots which are immobile.

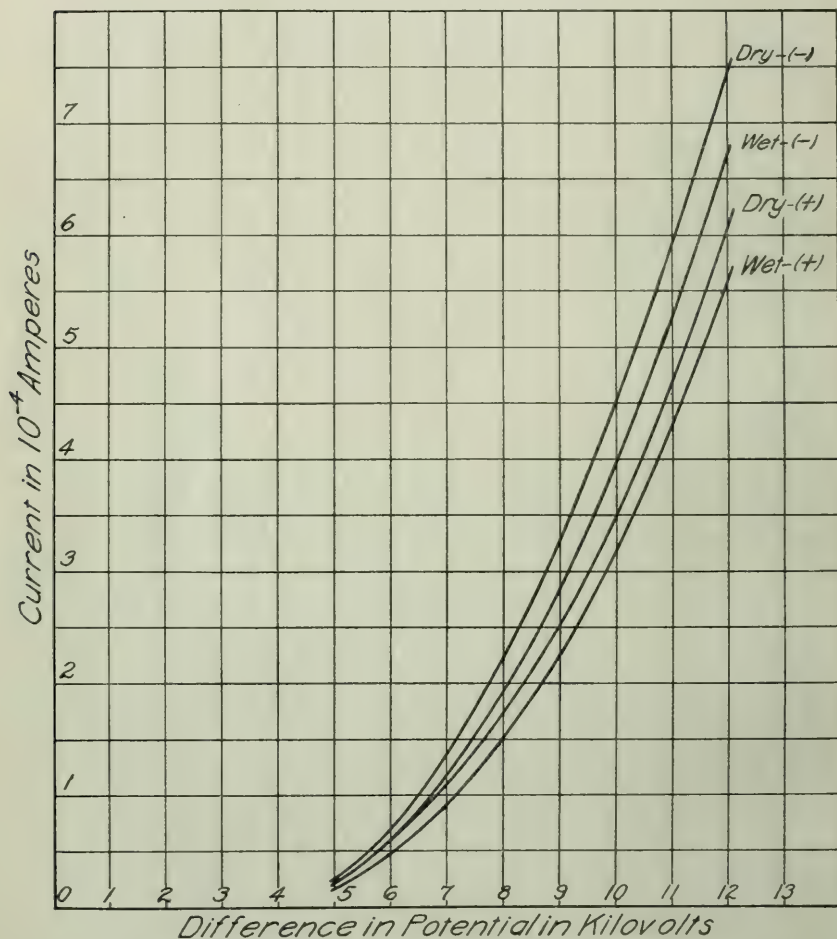


FIG. 19. EFFECT OF HUMIDITY UPON THE CORONA CURRENT

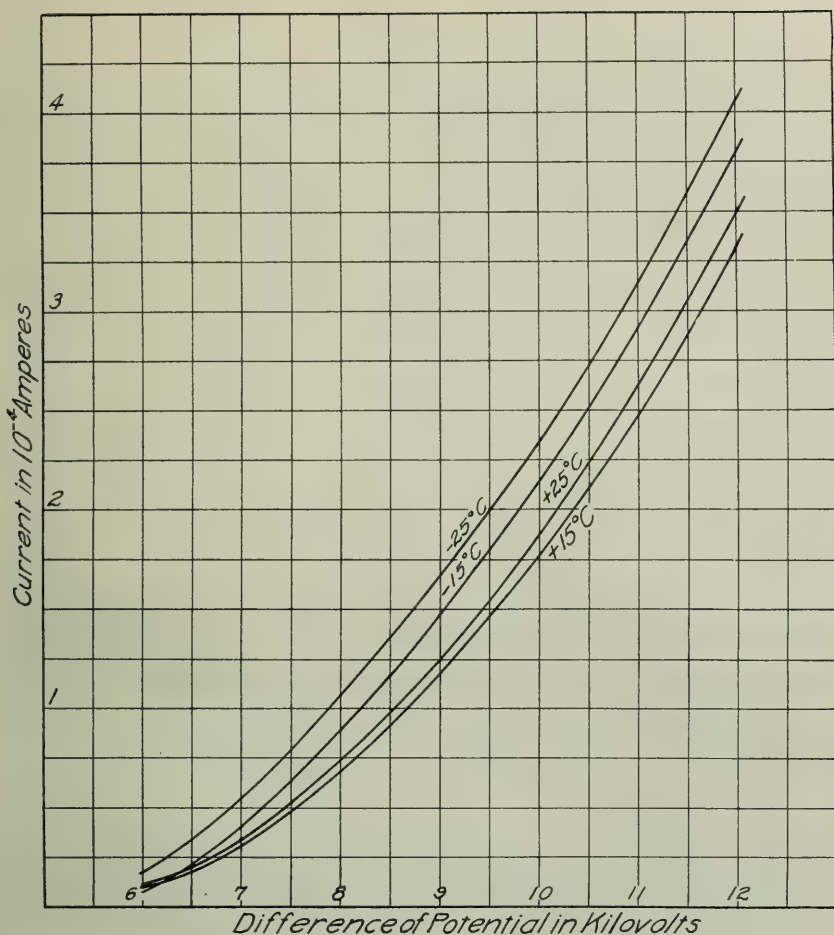


FIG. 20. INFLUENCE OF TEMPERATURE UPON THE CORONA CURRENT AT A CONSTANT PRESSURE OF 760 MILLIMETERS

The effect of moisture on the appearance of the negative discharge was shown by the following experiment: The tube was filled with moist air, and a voltage somewhat above the critical value was impressed. A mixed discharge resulted as was described in the preceding paragraph; then a current of dry air was started through the tube, and little by little the discharge cleared up and resolved itself into a line of uniformly spaced brushes which were in continual agi-

tation. When moist air was again admitted, the discharge resumed its former character.

With moist air in the tube and a fairly high potential difference the wire vibrates circularly for both polarities, and describes a torpedo-like figure of revolution. The filling of the tube with dry air diminishes considerably the amplitude of the vibration for wire positive and stops the vibration entirely for wire negative.

17. *Temperature.*—The influence of temperature upon the current for a No. 36 copper wire in a closed tube under a pressure of 760 mm. was determined for the temperatures 15 degrees C. and 25 degrees C. The results appear in Fig. 20. The lower temperature was obtained by placing cloths wet with alcohol upon the tube and directing a stream of air from a fan upon it. The curves indicate that this difference of temperature makes a far greater difference in the current for wire negative than for wire positive, both currents showing an increase for higher temperature as might be expected.

18. *The Nature of the Surface of the Wire and the Metal of the Wire.*—The fact that the starting point of the negative corona was influenced by dust particles on the wire suggested that a careful study should be made of the corona from different surfaces and from different wires: It was decided to use wires having polished, corroded, and mechanically abraded surfaces. The results will be shown in the following paragraphs:

(1) In the preparation of the polished surfaces care was taken in choosing wires without kinks or surface scratches. These wires were polished with fine emery cloth and finished with chamois and jeweler's rouge just before they were placed in the tube.

The abraded surfaces were prepared by rolling the wire in emery powder between two hard plane surfaces. Care was taken to have the surfaces abraded uniformly over the whole length.

The corroded surfaces were prepared by different methods. The surface of the steel wire was corroded by a solution of nitric acid, which made a black surface. The aluminum wire was corroded by allowing it to remain in a solution of sulphuric acid for a few days. The result was a thin white coating. For copper it was necessary to oxidize the surface by passing a heating current through the wire in

the presence of oxygen. Since ozone is produced by the corona discharge in air, the silver wire was coated with a layer of silver peroxide by allowing the corona to play on the wire for some time.

(2) The results of starting voltages for different surfaces and wires are shown in Table 2.

TABLE 2

COMPARISON OF STARTING VOLTAGES FOR DIFFERENT SURFACES AND WIRES
All wires about 0.41 mm. diameter

COPPER

Polished			Abrased			Corroded		
Press. mm.	Wire - + Volts.		Press. mm.	Wire - + Volts.		Press. mm.	Wire - + Volts.	
50	1 700	1 780	53.2	1 680	1 820	50.3	1 650	1 660
252	2 650	2 600	253	2 550	2 800	250	2 010	2 500
731	6 010	5 760	743	5 600	6 200			

STEEL

51.6	1 710	1 710	52.2	1 690	1 740	52.3	1 750	1 700
252.4	2 600	2 600	253.2	2 770	2 770	252	2 550	2 710
727.6	5 660	5 960	736	4 560	5 830	739.4	4 810	5 760

ALUMINUM

50	1 760	1 720	52	1 660	1 800	51.9	1 240	1 690
251	2 820	2 900	251.5	2 490	2 900	252	2 370	2 660
741.1	5 880	6 180	741	5 010	5 800	745.3	4 680	5 880

SILVER

53.2	1 850	1 820	52.3	1 730	1 740	52.5	1 850	1 780
252.1	3 150	3 050	252.2	2 600	2 900	252.2	3 150	3 000
744.8	4 210	6 130	743.2	5 060	5 850	746	5 760	6 320

The results shown in this table can be discussed for each of the surface conditions of the wire, and for each condition three pressures will be considered.

(3) The general appearance of the corona is the same for all polished positive wires and differs only slightly for negative wires at different pressures. At pressures of nearly 50 mm. when the potential is brought up to the glow potential, wire positive, a very faint flashing glow appears over the whole length of the wire and becomes uniform and steady as the potential is raised slightly. The potential may be carried up to the arcing point without changing the gen-

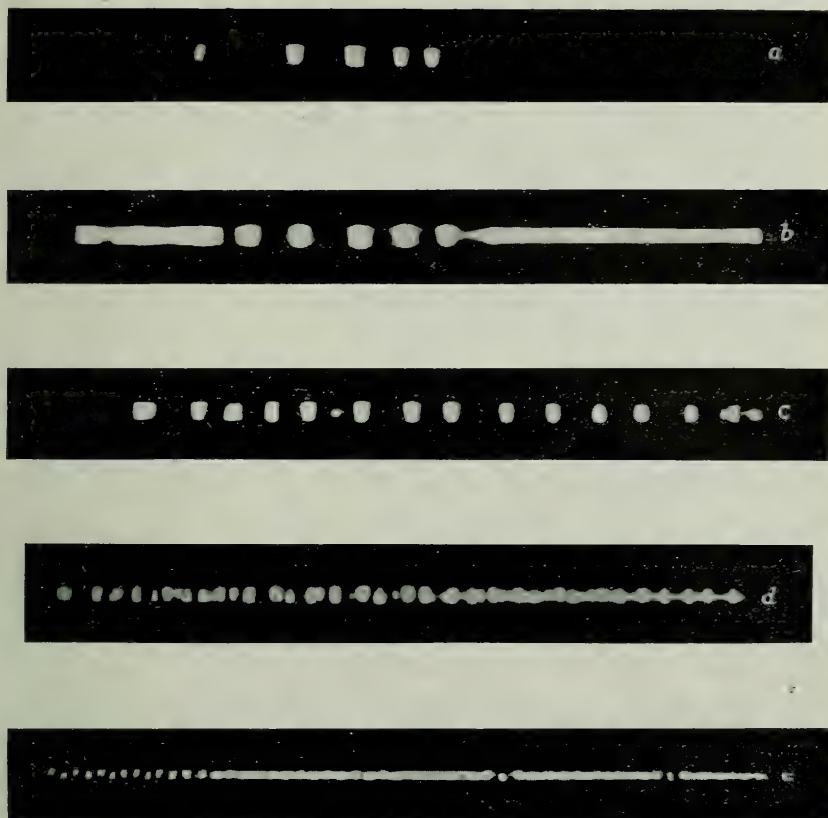
eral appearance of the uniform glow. The only noticeable change is an increase in the brightness of the bluish glow.

For pressures of 50 mm. and for negative wire, the first appearance of the corona is a flashing glow, similar to that for positive wire but of much greater diameter and brightness. Increasing the potential causes this glow to remain steady on the wire, to become uniform and to be very bright. Very little current flows until a stage is reached not far above the starting point, where the bright uniform glow breaks into large, clear, characteristic, negative beads. The current then increases rapidly with the potential. As the potential is increased the beads increase in number but remain large and well defined.

For the polished surfaces and with a pressure of 50 mm. the negative corona on copper begins at a lower potential than the positive. Corona appears at the same potential for both polarities in steel, but for aluminum and silver the positive glow begins at the lower potential. Table 2 shows no general law. With the exception of the silver wire at a pressure of 746 mm. the starting potential for the corroded wire is smaller for both polarities than for the polished wire. For the negative abraded wire the starting point is in general lower than for the polished wire with only two exceptions. With the exception of silver the starting point of the abraded positive wire is higher than that of the polished wire. With increasing pressure the differences involved by abrasion and corrosion diminish. The largest influence is found for aluminum wire, negative corroded at 51 mm.

For pressures of nearly 250 mm. the glow for wires positive is the same as for pressures of 50 mm., being uniform and increasing in brightness as the potential increases. For wires negative and polished it is almost impossible to break the glow up into clear-cut beads at this pressure. With increasing potential the glow becomes brighter and condenses at certain ill-defined points, apparently attempting to form beads, but these condensed regions move rapidly back and forth along the wire.

For atmospheric pressure, wires polished and positive, the glow appears faint but uniform and increases in brightness as the potential is increased. For negative wires a faint flashing glow appears at break-down potentials and increases in brightness with the potential increase. A very few scattered beads form at times, but they are small and unstable with very rapid lateral motion. This motion



Abrased

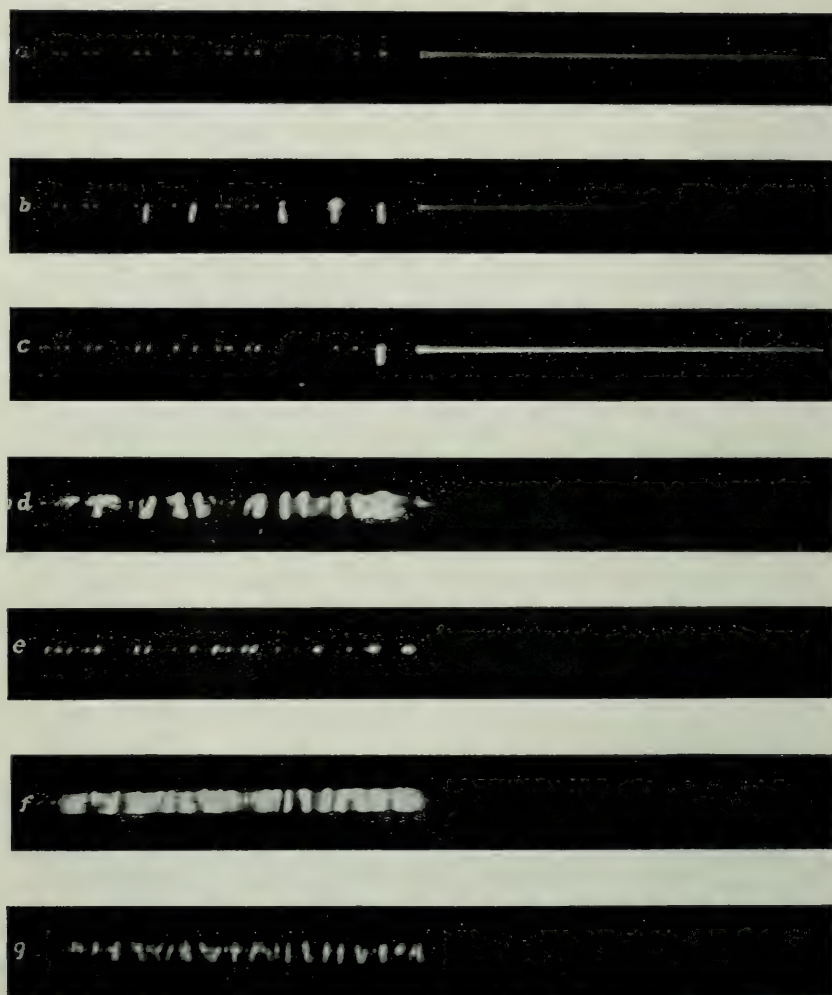
Polished

Corroded

Steel Wire, 0.28 mm., Diameter
All Wires Negative

	Voltage	Pressure
a	990	21 mm.
b	1080	25 mm.
c	1400	39 mm.
d	2300	68 mm.
e	8900	370 mm.

FIG. 21. A COMPARISON OF THE GLOW ON ABRASED, POLISHED, AND CORRODED SURFACES OF STEEL WIRE



Enameled

Polished

German Silver Wire, 0.65 mm., Diameter

		Voltage	Pressure
a	Wire +	1460	23.5 mm.
b	Wire +	1700	25.5 mm.
c	Wire +	1830	35.5 mm.
d	Wire +	2800	91.5 mm.
e	Wire -	3920	185.5 mm.
f	Wire +	4400	185.5 mm.
g	Wire +, Arc in Series	4450	185.5 mm.

FIG. 22. A COMPARISON OF THE GLOW ON ENAMELED AND POLISHED SURFACES OF GERMAN SILVER WIRE

increases in amplitude and speed with increasing voltage. Clear cut beads over the whole wire are impossible here as in the last case.

(4) With wire surface mechanically abraded or roughened and pressure of 50 mm., the positive glow begins with faint flashes as with the polished surfaces; then becomes steady and uniform and increases in brightness as the potential is increased. The starting glow voltage is in general higher than for the positive polished wires, and is also higher than for the abraded negative wires. For wires abraded and negative the corona begins with bright flashes of a fuzzy glow, part of which may have one or two large flashing beads. This flashing glow seems to pulsate in synchronism with the impulses of the driving machinery. A slight potential increase above the first noticeable glow causes the glow to break into well-defined beads which soon become steady and clear and which increase in number with a potential increase. The negative starting voltage for abraded wires is lower than for the polished surfaces.

For wires abraded and pressure of 250 mm. the positive visual glow is the same as for pressure of 50 mm. The positive starting potential is in general higher than for the negative abraded and also positive polished surfaces. The negative glow voltage causes very faint "spears" or small brushes of light to flash from sharp points here and there on the rough surface. These spears increase in size and number with increased potential, some being much brighter than others. As the potential is increased these spears unite into definite, clear beads which at times may be very steady and at other times may have more or less violent lateral movements. The negative starting voltage for abraded surfaces is much smaller than for the polished surfaces.

At atmospheric pressures the positive glow on the abraded wire surfaces usually begins with a few small flashing purple streamers or brushes extending from the wire almost to the tube. These streamers are similar in appearance to the positive fans and to the streamers emitted from the surface of the enamel covered wire, Figs. 21 and 22. These streamers increase in brightness and are accompanied by a soft glow as the potential is increased. After a certain increase in the voltage has taken place, these streamers disappear and only the uniform glow remains and increases in brightness.

For the abraded negative wire at atmospheric pressure the corona starts with small flashing spears the same as for the abraded wire at

250 mm. These spears increase in number very rapidly with an increase in voltage, some of them collecting, so to speak, into small bright beads and then breaking up again. As the potential continues to increase, the beads become more steady and definite, so that at times the abraded wire may be covered with many small, bright, steady, and evenly spaced beads.

(5) The positive visual corona for corroded surfaces is essentially the same for all pressures as has been described for the abraded surfaces. At low pressures it begins with a faint flashing glow which becomes steady and uniform and which increases in brightness. At pressures of 250 mm. the appearance is the same as described for the abraded surfaces, and for atmospheric pressure the corona may start with the small purple brushes or fans and an accompanying flow, the fans soon disappearing and the glow becoming uniform and increasing in brightness. The positive glow generally begins at lower voltages for the corroded surfaces than for the polished surfaces.

The negative visual corona for the corroded surfaces is likewise similar to that for abraded surfaces at different pressures. Clear cut and steady beads are obtained at the lower pressures but are not so stable for the higher pressures. In general the negative starting voltage is lower than for polished surfaces.

(6) In order to show a few results photographically a wire having one-third of its length polished, one-third corroded, and one-third mechanically abraded was placed in a tube with a longitudinal slot, and photographs were taken when the corona was on the wire. Fig. 21 contains photographs of the negative wire, the left end being abraded, the center polished, and the right end chemically corroded.

These photographs show that the beads begin on the polished surface, that the corroded surface shows no glow, and that the abraded surface has only a slight brush discharge on it. The beads on the polished surface are very large, clear, steady, and evenly spaced. Fig. 21, *b* shows the effect of a slight increase in voltage where the glow now appears on the corroded surface and the beads begin to form on the abraded surface. Gradually increasing the voltage and the pressure as well causes the glow to become brighter on the polished surface and the beads to increase in number on the abraded and corroded surfaces. The beads on the abraded portion have a lateral movement, while those on the polished part are still very steady and clear.

With a still greater increase in pressure and voltage it is possible to reach a condition where the whole length of the wire is covered with clear, steady, and evenly spaced beads (Fig. 21, *c*). Here it seems that the surfaces all act very nearly the same in the formation and building of the corona discharge.

When the pressure is increased to 370 mm. and the voltage is sufficiently high to produce the discharge, the corona starts first on the abraded portion and only on this part can steady, clear beads be obtained (See Fig. 21, *e*). The beads on the corroded part are fairly well defined, but they are in an agitated state. Under these conditions it is found impossible to get steady beads on the polished part of the wire; instead of the clear beads there is a rather knobby glow on the wire, the condensations in which seem to be beads trying to form.

This reversal of the phenomena, the clear beads forming on the polished surface at low pressures and on the abraded surface at high pressures as shown in Fig. 21, actually occurred for steel wire. The corona starts first on the polished wire for low pressure and begins on the abraded or corroded wire at much lower potentials for high pressures.

An enameled german silver wire was fitted into the tube after half of its length had been freed from the enamel and polished. At low pressures for the positive wire the characteristic glow appeared on the polished end. The enameled end had several small starlike spots of light which were irregularly distributed and which appeared at points where the insulation had failed. Keeping the wire positive and increasing the voltage caused very bright "streamers" of purple light to shoot from a few of these small stars. At higher pressure and higher voltage these streamers increased greatly in number, the glow spreading out into a thin fan-shape. This fan slowly oscillated about the bright spot on the wire as a center. Between the fans a hazy fog-like glow was present. When an arc was placed in series with the wire and the tube, this fog disappeared and the fans became more sharply defined and steadier than they were.

For the wire negative (see Fig. 22, *e*) it was not possible under any conditions to get the characteristic negative beads nor could a glow be produced on the polished end. The only discharge present was on the enameled end and was similar in appearance to the small stars for the positive wire. For the negative wire, however, the stars were intensely bright and in slight movement. Fig.

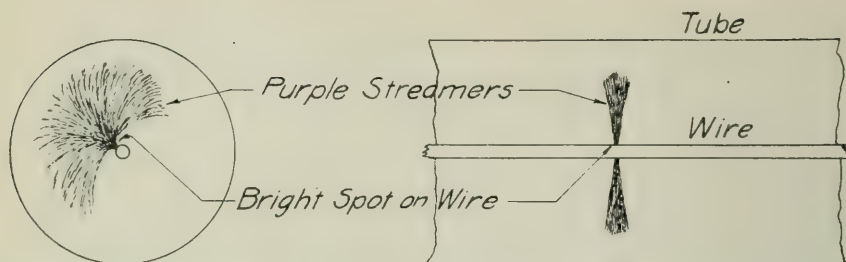


FIG. 23. STRUCTURE OF THE POSITIVE PURPLE FANS, UNDER CONDITIONS GIVEN IN FIG. 22.

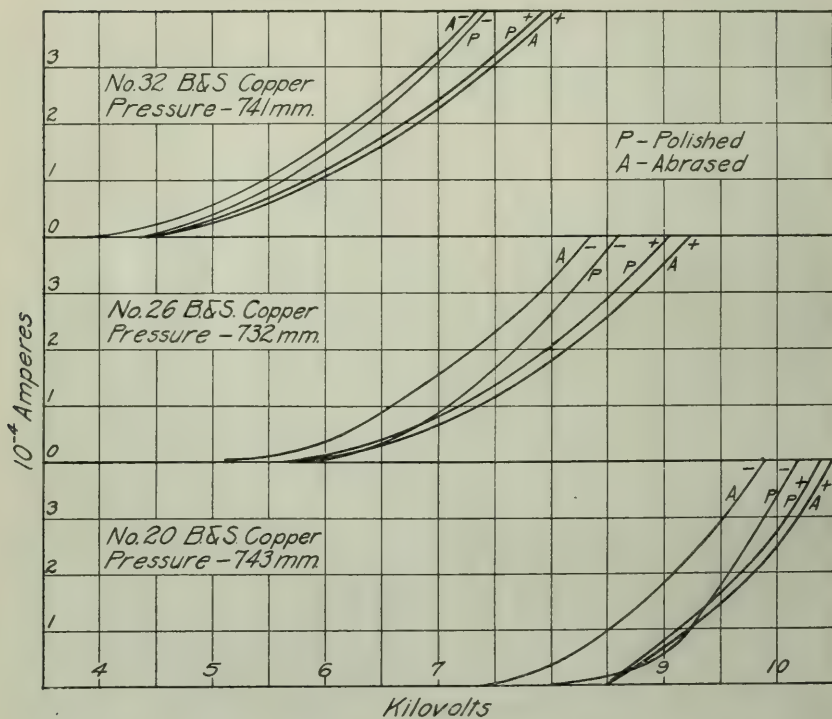


FIG. 24. CHARACTERISTIC CURVES FOR COPPER WIRES WITH VARIOUS RADII AND SURFACES

22 shows the appearance of the discharge from the enameled wire when it is both positive and negative. Fig. 23 gives details of the structure of the positive purple fans. For the enameled wire negative the starting potential was much lower than for the opposite polarity.

(7) The curves in Fig. 24 are taken for varying sizes and different surfaces of copper wire.

In *e*, Fig. 22, the surprising fact is shown that the negative discharge passes through the enameled part of the wire, while the free metal surface shows no trace of a glow. The curves show that the effect of abrasion in general lowers the starting point for copper wires at atmospheric pressure. The curves for the negative abraded wire are widely displaced from those of the polished wire; thus it is shown more current flows in the corona discharge for the same voltage for wire abraded than for the smooth wire. The curves showing the discharge for the positive abraded wire quickly cross those for the polished wire and then continue to rise slightly displaced, less current flowing for the same potential abraded than for polished. The abraded surface has, thus, the effect of restraining the flow of the positive current.

The effect of abrasion is much greater in the negative than in the positive current. The curves also show that this effect is greater for the larger wires, as might be expected. The higher starting potential for the larger wires is also evident.

The negative current builds up very slowly at first on the polished surface but finally reaches a point where it builds up much faster than the positive, and at this point the beads are formed. The starting voltage for the abraded surface negative is much lower than for polished surface negative. The characteristic curve of the abraded wire is a smooth rising one which eventually crosses the polished negative curve for large current values. This same phenomenon has been observed for different metals.

Fig. 25 gives the characteristic positive and negative curves for aluminum wires at about 50 mm., and shows the effect of the three surface conditions,—namely, polished, abraded, and corroded. The starting positive wire voltage for the smooth surface is slightly lower than that of the negative, but the curves cross low, the positive current building up slowly with increased potential while the negative curve is almost a straight line which rises very rapidly. The positive

starting potential is higher for the abraded surface than for the polished, while that for the negative abraded surface is lower. The negative polished and abraded surface curves cross, but the positive do not. For the corroded surface the positive glow voltage is about the same as for the polished surface, the curve for the former condition becoming displaced shortly, less current flowing for the same voltage. The negative starting potential is very much lower in the latter case than that for the polished surface, but crosses at a low current value and rises to the right, less current flowing for the same potential.

Thus it is seen that the surface condition has a very marked

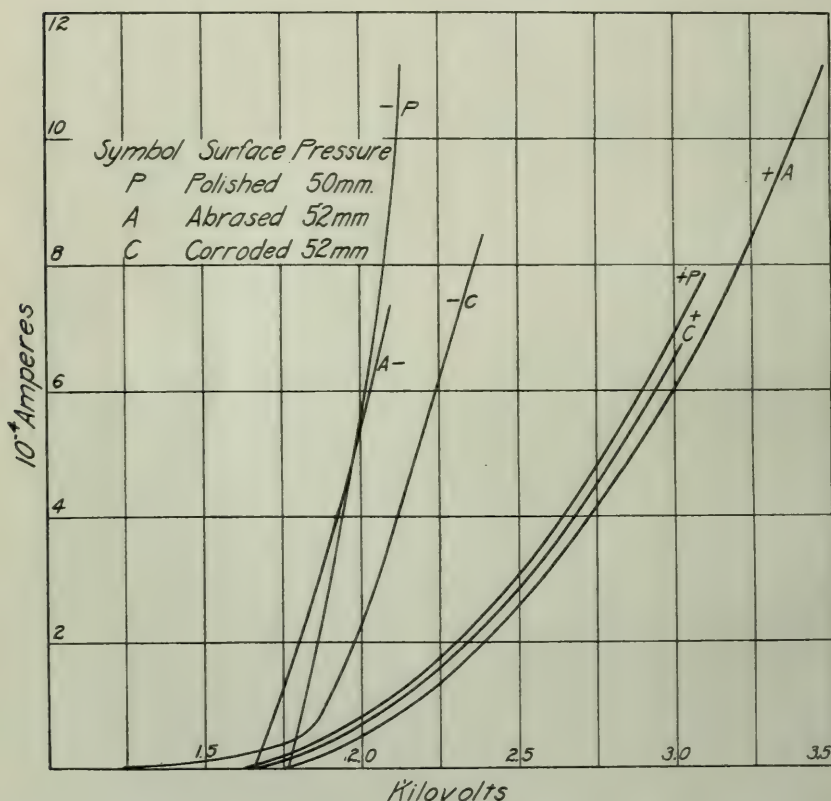


FIG. 25. CHARACTERISTIC CURVES FOR ALUMINUM WIRE OF 0.45 MM. DIAMETER WITH VARIOUS SURFACES

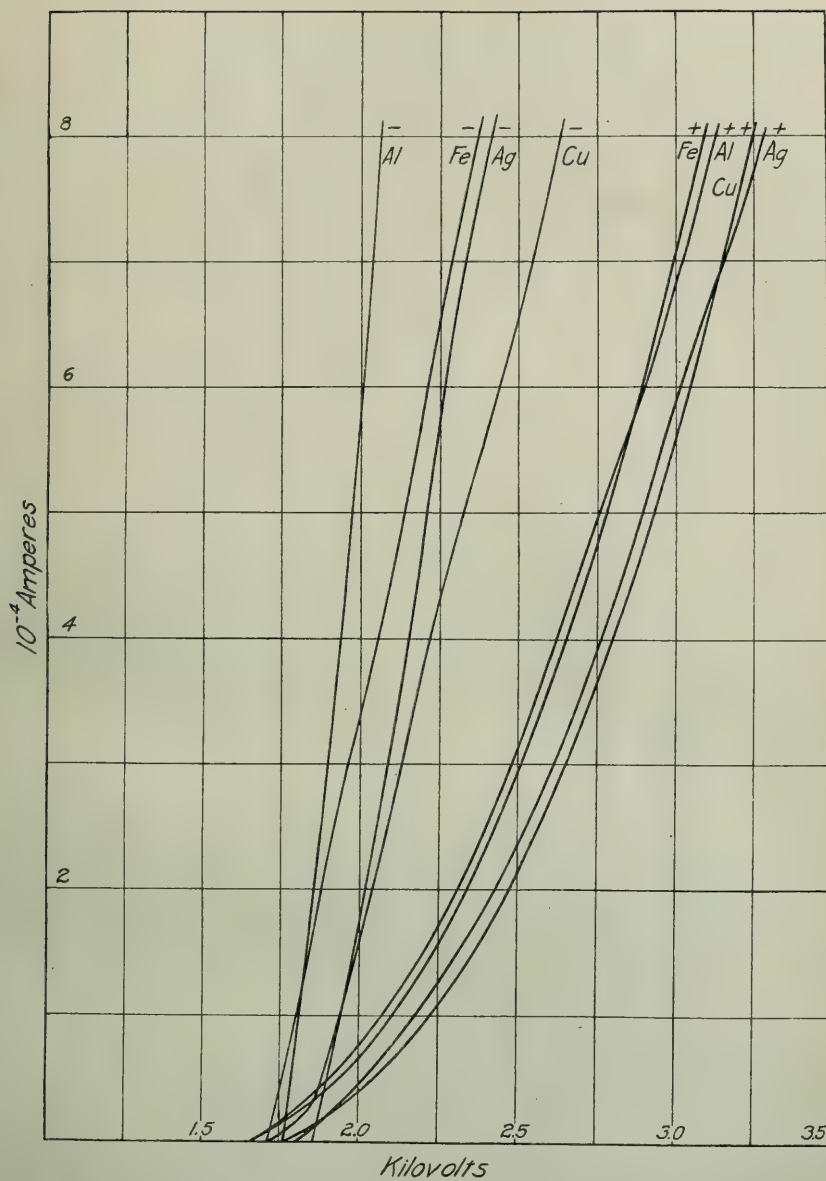


FIG. 26. A COMPARISON OF THE CHARACTERISTIC CURVES SERIES OF DIFFERENT METALS

effect on the starting point of the corona as well as on the characteristic curves. All the wires were about 0.41 mm. in diameter. In general the abraded surface has the effect of lowering the starting potential for negative wire and raising it for positive wire. The starting point for both positive and negative corona in the case of corroded wires is in general lower than that for the polished surfaces, but the corroded surface characteristics behave in rather an erratic manner, sometimes being displaced in one way and sometimes in the opposite.

Table 3 gives a comparison between the corroded and polished wire characteristics for both positive and negative surfaces at different pressures.

The curves in Fig. 26 show a comparison between the characteristics of different metals. Very marked differences are evident in the characteristic curves and show directly that the metal itself has a

TABLE 3

COMPARISON OF CORRODED WITH POLISHED WIRE CHARACTERISTICS

COPPER			
Wire	Press	Starting Pot.	Corroded Surface Characteristic
-	50.2	Lower	Raised
+	50.4	"	"
-	250.0	"	Crosses high
+	250.8	"	Raised
STEEL			
-	53.2	Higher (press. diff.)	Crosses high
+	52.4	Lower	"
-	252.0	"	" low
+	252.4	"	Lowered
-	739.4	"	Crosses high
+	739.4	"	" low
ALUMINUM			
-	51.9	Lower	Crosses low
+	51.9	"	"
-	252.0	"	" midway
+	252.0	"	Raised
-	745.3	"	Crosses midway
+	745.4	"	Raised
SILVER			
-	52.5	Same	Lowered
+	52.5	Lower	"
-	252.2	Same	Crosses low
+	252.2	Lower	" midway
-	745.8	Higher	Lowered
+	746.1	"	"

part to play in the corona formation. The positive and negative characteristics, especially for aluminum, become widely separated for large currents. The curves for the other metals separate at different rates for increasing current values, but in such a manner that each metal behaves in its own characteristic way.

Slight differences in the starting points for the different metals were noticed; these differences, however, are of such a nature that they cannot be explained as being experimental errors. Steel and copper seem to have about the same starting point, while that for aluminum is a little higher and silver has a value still greater. The different metals not only affect the behavior of the characteristic curves but also the starting points of the corona glow.

The formation and number of the negative beads depend not only on the pressure and potential, but also on the surface condition and the material of the wire. The current per bead is larger for the abraded and corroded surfaces than for the polished surface, with the assumption that the whole current is to be carried by the beads. For an increase in pressure it is also seen that the current per bead is much less for the polished surface than for the others, but the beads are smaller in size. For the higher pressures it takes, however, a larger voltage to produce the same number of beads. For the lower pressures the beads have about the same degree of stability for all the different surfaces, while for higher pressures the beads are more stable on the abraded or corroded surfaces than on the polished, it being almost impossible to get definite beads on the polished wire for atmospheric pressures.

The number of beads increases rapidly with increasing voltage. Here again the effect of the materials is compared. For the production of the same number of beads it takes in general a greater voltage on the steel than on the copper and aluminum wires.

CHAPTER VI

ALTERNATING CURRENT RECTIFICATION

19. *Suggested by a Comparison of the Air and Hydrogen Characteristic Curves.*—Fig. 9 shows that the discharges through air and hydrogen were very similar in so far as the variation between critical voltage and radius and pressure are concerned. The curves in Fig. 27 show clearly the difference between the corona in air and in hydrogen. The two curves on the left side of the figure refer to

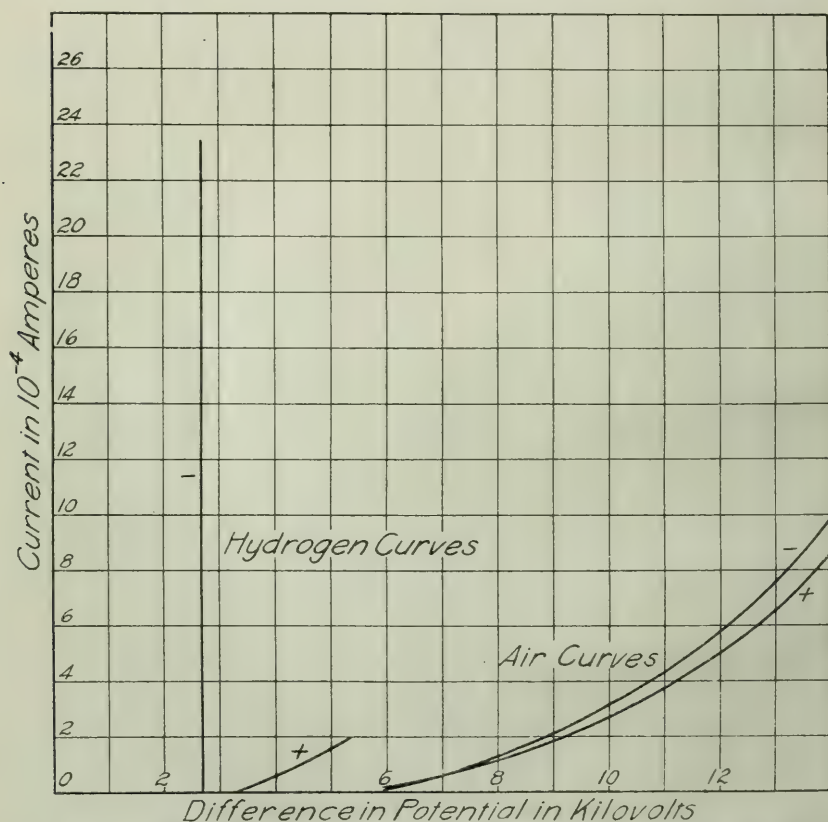


FIG. 27. COMPARISON OF CORONA IN AIR AND HYDROGEN UNDER SIMILAR CONDITIONS

hydrogen, while the curves on the right show results obtained with air. The data for these curves were obtained with wires of approximately the same diameter. These curves show two distinct differences between corona in air and in hydrogen.

In air the positive corona starts at a lower voltage than the negative, while the reverse is true when the dielectric is hydrogen. The other and more important difference is the entire dissimilarity of the positive and negative curves with hydrogen. This difference has not been found with air. A single glance at this curve shows that corona in hydrogen between a wire and a tube is an effective means of accomplishing rectification. This statement is true since large currents may be obtained from a negative wire with voltages which will give little or no current from a positive wire. This rectification may be accomplished with the wire cold and is not a case of rectification by means of a hot cathode. The principal of electron emission from a hot cathode might be used, however, in connection with the corona rectification.

20. *Description of Apparatus and Tests.*—To show that rectification was possible the corona tube was connected to an alternating source of voltage. A sensitive oscillograph element was connected directly in series with the corona tube and another element was connected across the primaries of the transformers. A diagram of the connections is shown in Fig. 28.

21. *Oscillograms and Their Interpretation.*—Fig 29 gives the current and voltage curves when an alternating voltage is impressed across a corona tube. The curve having both positive and negative lobes represents the voltage. The non-symmetrical character of this curve is due to the drop in the resistance in series with the primaries of the transformers. The curve lying mainly below the axis represents the current flowing between the wire and tube. The part of this curve slightly above and slightly below the axis is of the same shape and order of magnitude as the charging current of the condenser formed by the wire and cylinder. This fact was determined by an oscillogram taken at a voltage slightly less than that necessary to form corona.

The voltage at which negative corona starts, as shown in this oscillogram, is approximately twice the voltages across the tube at the instant that the discharge ceases.

The rectification with corona in hydrogen is practically perfect as is shown by the oscillograms in Figs. 29 and 30.

In an investigation, interrupted by the World War, J. W. Davis has shown that alternating currents may be perfectly rectified up to 42,000 volts made effective by means of the corona in hydrogen. The rectification is, however, not of very high efficiency as a large part of the energy is transformed into heat in the corona tube. For a given gas pressure the maximum voltage which may be rectified or, in other words, the voltage at which the arc sets in between the coaxial cylinders is nearly directly proportional to the radius of the outer cylinder, when the radius of the inner cylinder is small compared with that of the outer cylinder. In order to improve the efficiency of the rectification the central wire was heated. An incandescent wire gave rise to the corona discharge at voltages much lower than those necessary to start a discharge from a cold wire. The initial state of ionization around the wire has a very marked effect on the critical corona voltage. When the central wire is heated to incandescence and then the high voltage applied, the temperature of the wire will change very much, especially towards the ends where the wire appears almost dark, while in the middle the temperature may fall to that of dull red heat. This fall of temperature is undoubtedly due to the wind set up in the corona. Fig. 31, from Davis' unpublished paper, will show a rectification at 42,000 volts.

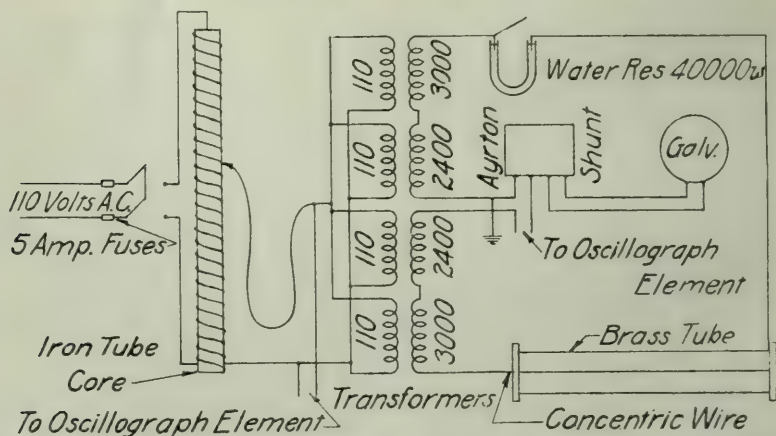


FIG. 28. DIAGRAM OF CONNECTIONS FOR ALTERNATING CURRENT RECTIFICATION IN HYDROGEN

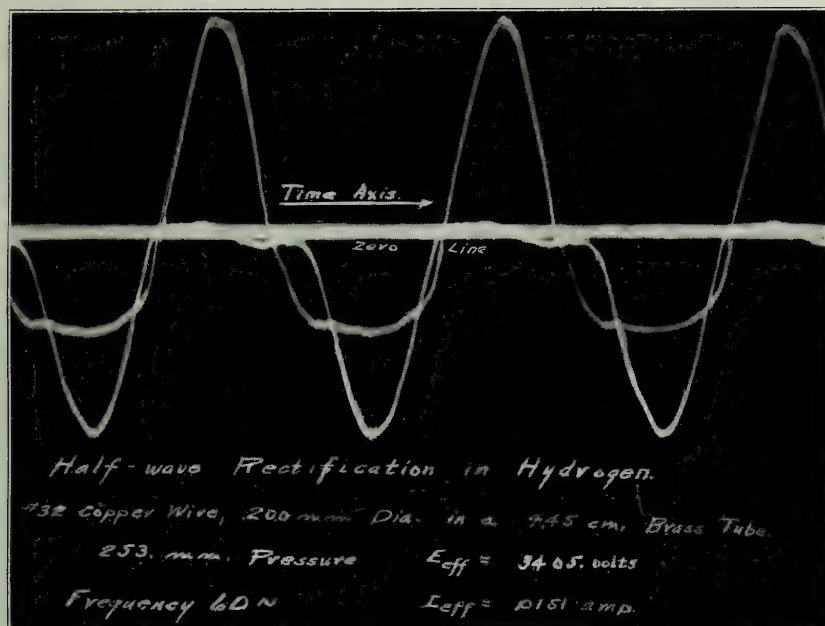


FIG. 29. OSCILLOGRAM

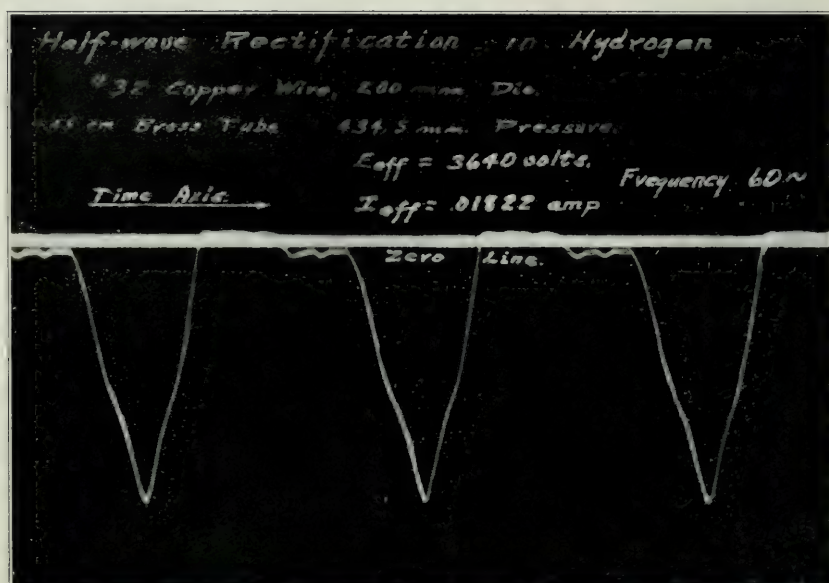


FIG. 30. OSCILLOGRAM

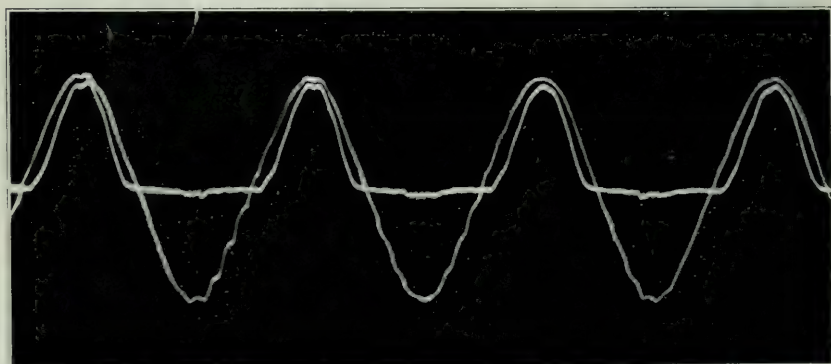


FIG. 31. OSCILLOGRAM SHOWING RECTIFICATION AT 42,000 VOLTS

CHAPTER VII

DISTRIBUTION OF POTENTIAL IN THE CORONA TUBE

In order to develop any complete corona theory a knowledge of the distribution of the potential between the electrodes is necessary. The distribution of potential between the wire and the coaxial cylinder was investigated in the following manner.

22. *Method. and Apparatus.*—A hole was drilled in the side of a cylinder, and an insulated wire terminating in a bare spherical tip was arranged so that it could be moved radially between the wire and the tube. A micrometer microscope directed on a fixed point of the movable wire served to determine the relative position of the point. An electrostatic voltmeter of small capacity was connected in series with the exploring point and the tube.

When the point was moved to any position in the radial field, the voltmeter quickly showed a constant deflection and indicated that the potential of the point was in equilibrium with that of the field at that particular place. By moving the exploring point from the tube

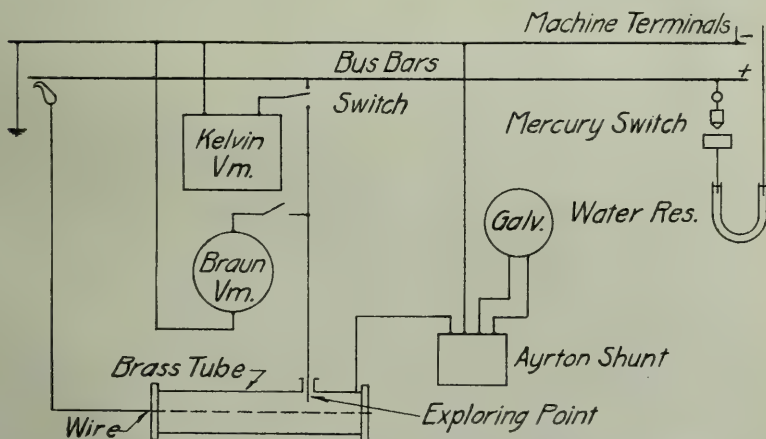


FIG. 32. DIAGRAM OF CONNECTIONS OF APPARATUS FOR DETERMINING THE DISTRIBUTION OF POTENTIAL IN THE CORONA TUBE

to the wire and observing the voltmeter readings at certain intervals, one obtained a comparatively accurate estimate of the intensity of the field. The apparatus and connections are shown in Fig. 32. The tube used in this investigation was 35.5 cm. long and 7 cm. in diameter. The wire was copper, well polished, and stretched tightly. In all, four wires were used, No. 40, No. 32, No. 28, No. 20, B. & S. gage. Since it was necessary to work at pressures lower than atmospheric,

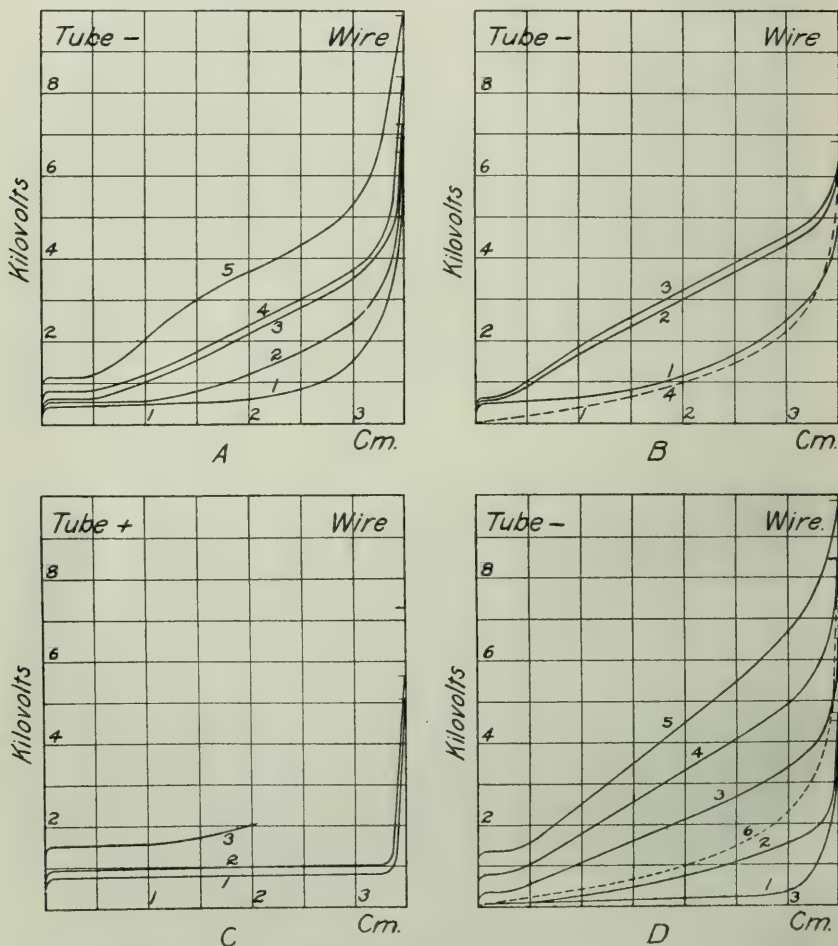


FIG. 33. REPRESENTATIVE CURVES SHOWING DISTRIBUTION OF POTENTIAL IN THE CORONA TUBE

a glass tube was sealed over the exploring rod and arranged with ground points and springs so that the point might move at will without destroying the constant pressure.

23. *Results Obtained.*—By this method, curves were taken for various pressures and voltages after the appearance of the corona. Representative curves are shown in Fig. 33, and the conditions under which each curve was taken are given in Table 4.

For the smaller wires it was found difficult to obtain data for curves when the wire was negative, because the voltmeter would not come to rest and give a definite reading. For a No. 32 wire, when the wire was negative, two curves shown in Fig. 33C were taken before the corona appeared, also a portion of a curve for a voltage at which there was a distinct series of beads along the wire.

Curves were also obtained for No. 28 and No. 20 wire when the wires were negative, the same general characteristics being exhibited in each.

Curve 4, Fig. 33B, shows the distribution of potential as given by electrostatic theory. This theory assumed, of course, that there are no charges in motion in the gas: that is, that there is no current. It is seen that the actual distribution is very different from what it

TABLE 4
TABLE OF DATA FOR CURVES

Figure	Curve	Wire B. & S. Gage	Voltage	<i>I</i> Amperes	<i>P</i> Mm. of Hg.	Temp. C.	Remarks
33A	1	32	6 510	$4.17.10^{-8}$	747	25°	No glow
	2	32	6 825	$1.91.10^{-6}$	747	26°	Distinct glow
	3	32	7 425	$1.91.10^{-5}$	747	26°	Good glow
	4	32	8 400	$5.94.10^{-5}$	747	26°	Good glow
	5	32	9 900	$9.54.10^{-5}$	747	26°	Bright glow
33B	1	32	6 825	$1.91.10^{-6}$	747	26°	Distinct glow
	2	32	6 825	$2.03.10^{-4}$	241	24°	Bright glow
	3	32	6 825	$3.46.10^{-4}$	885	24°	Brilliant glow
	4	32	6 825	Electrostatic curve			
33C	1	32	5 050	$1.79.10^{-8}$	744	26°	No glow
	2	32	5 650	$2.39.10^{-6}$	744	26°	A few dull beads
	3	32	7 250	$3.10.10^{-5}$	744	26°	Beads 1 cm. apart
33D	1	40	4 520	$4.77.10^{-8}$	740	22°	No glow
	2	40	4 700	$1.19.10^{-6}$	740	22°	Distinct glow
	3	40	6 500	$2.26.10^{-5}$	740	22°	Good glow
	4	40	8 400	$8.29.10^{-5}$	740	22°	Good glow
	5	40	9 900	$1.67.10^{-4}$	740	22°	Brilliant glow
	6	40	8 400	Electrostatic curve			

would be if there were no current. The detailed discussion of the curves will be considered under the two polarities.

In general for the positive wire the space between the anode and the cathode may be broken up into four regions:

(1) A region immediately surrounding the wire, which is characterized by a very large potential gradient. This gradient may be due to the excess of the number of ions or electrons approaching the electrode over the number of those leaving, since the former number includes ions generated at all parts of the field; whereas the latter contains only ions that are generated in the narrow layer close to the wire. It is, therefore, evident that the charges on the excess of negative ions near the wire disturb the electric field so that the potential difference per centimeter, or the gradient, is large near the surface of the wire.

(2) A region of approximately constant force extending from the "surface layer" region adjacent to the wire to a point which varies with the pressure, current, and voltage. At the higher voltages, the actual potential at a given point in this region is greater than the theoretical electrostatic potential, and the tangent to the curve may be either greater or less.

(3) A region of little or no force near the tube, but not touching it.

(4) A region adjacent to the tube, where positive charges accumulate and form an abrupt cathode drop of potential.

When the wire is negative and corona appears, a potential curve is obtained which differs somewhat from the positive curves. Large cathode and anode drops appear, and the intervening space has a very small field. Reasoning similar to that which explains the shape of the curves when the wire is positive explains the negative curves.

So in general, the anode and cathode drops of potential are predominant in both types of curves. There are several reasons for this: namely,

- (1) Polarization potential between a metal and a gas.
- (2) Accumulation of ions.
- (3) Reflection of ions.
- (4) Different velocities of positive and negative ions.
- (5) A non-uniform field.

For a system where the potential at a point is due to moving charges as well as static charges, there is Poisson's equation expressing the density in terms of the potential

$$\Delta^2 V = -4\pi\rho,$$

or, expressed in cylindrical coördinates,

$$\frac{\delta^2 V}{\epsilon r^2} + \frac{1}{r} \frac{\delta V}{\delta r} + \frac{1}{r^2} \frac{\delta^2 V}{\delta \phi^2} + \frac{\delta^2 V}{\delta z^2} = -4\pi\rho$$

For this particular case, the derivatives in z and ϕ are zero; so rewriting this equation and using total derivatives gives

$$\frac{d^2 V}{dr^2} + \frac{1}{r} \frac{dV}{dr} = -4\pi\rho = \frac{1}{r} \frac{d}{dr} \left(r \frac{dV}{dr} \right). \quad (8)$$

Since the density is an undetermined function of the radius, the equation cannot be integrated directly. If, however, the potential is plotted against the distance from the axis, a graphical method will aid in the determination of the density; that is, if the first derivative

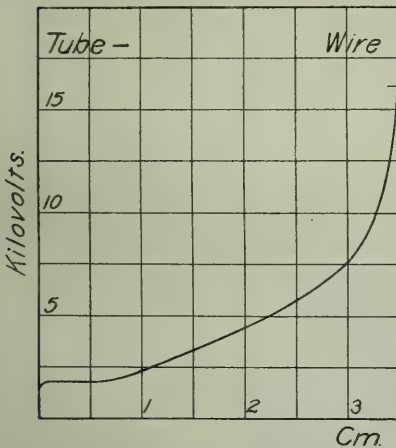


FIG. 34. EXPERIMENTAL CURVE OF DISTRIBUTION OF POTENTIAL IN THE CORONA TUBE

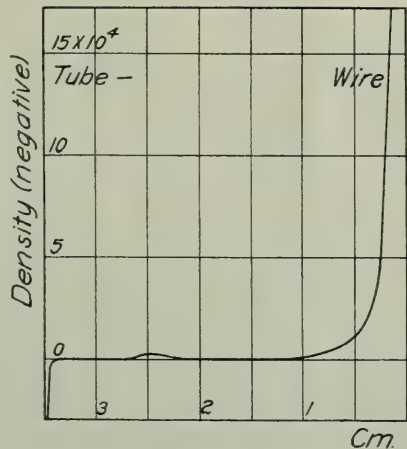


FIG. 35. COMPUTED CURVE OF THE VOLUME DENSITY OF ELECTRIFICATION IN THE SPACE BETWEEN THE WIRE AND THE TUBE

of the potential is determined from the curve for a series of values of r , these new values may be plotted against the radius again. Repeating this process with the derived curve gives a relation between the second space derivative and the radius. From these two derived curves, then, the density may be computed according to equation (8).

Fig. 34 is a curve of the same type as curve 4 in Fig. 33A, and Fig. 35 shows the density as computed for the different values of r .

The density curve shows that which was deduced intuitively in regard to the changes necessary to produce the observed distortion of the field. The large resultant negative charge near the positive wire and the positive charge near the negative tube should be expected. A peculiar maximum appears about 2.7 cm. from the wire.

Sources of error are found in the potential assumed by a sphere in an ionized gas. It is difficult to draw conclusions concerning the absolute potential of a sphere in a conducting gas, since it is very likely that the potential at an undisturbed point in a gas is not the same as the potential assumed by a sphere when its center is at this point.

In a sphere near the positive electrode, the potential being initially the same as that of the gas, two streams of ions move in opposite directions past the side of the sphere, one containing a large number of negative ions and the other a smaller number of positive ions. The sphere intercepts more negative ions than positive so that its potential falls below that of the surrounding gas. The charge thus acquired by the sphere increases until the effect which it produces in attracting positive and repelling negative ions causes them to come in contact with the sphere in equal numbers. The final value of the potential assumed by the sphere is too high by an amount which depends upon the relative velocities of the positive and negative ions.

Conversely, when the exploring sphere is close to the negative electrode, there is a greater number of positive than negative ions intercepted so that the potential of the sphere rises above the potential of the undisturbed gas, until finally an equilibrium is reached. The number of positive charges acquired by the sphere is equal to the number of negative charges; thus the potential assumed by the sphere is greater than that of the undisturbed gas. If, however, the velocity of the positive ions is approximately equal to that of the negative ions, the exploring point should attain very nearly the same potential as that of the surrounding gas. For the pressures used in this

series of experiments, the velocities of the ions are nearly the same. The error introduced could not, therefore, have been very great.

A slight error might be introduced if there were an appreciable voltmeter leakage between the point and the power line. The shape of the point also affects that of the potential curve to a small degree. The voltmeters used were practically free from leakage, and the work was done during cold, dry weather; so the error introduced from this cause is negligible.

CHAPTER VIII

THE PRESSURE INCREASE IN THE CORONA

Dr. S. P. Farwell was the first investigator to discover that at the instant the corona appeared on the wire the gas pressure in the corona tube increased. The increase appears very suddenly and also disappears very rapidly. For these reasons all the experimenters working in this laboratory have maintained that the pressure increase could not be due to heat. It has been suggested that it might possibly be due to ionization. This assumption is a possible consequence of the present theories of the corona, which assume it to be an ionization phenomenon. These theories assume that the high potential differences cause the few ions which are always present in a gas to move with a velocity sufficiently great to break the molecules with which they collide into two parts, one bearing a positive and one a negative charge. All these charged particles then move, because of the influence of the field, toward one or the other of the terminals. The presence of these ions thus explains the conductivity of the gas, and the acceleration of the ions explains the light effect. If the corona is an ionization phenomenon one would expect, provided the corona apparatus were enclosed, at the instant the corona appeared; i. e., at the instant the molecules were broken into ions, that the pressure in the apparatus would increase, because according to kinetic theory the greater the number of particles in a given volume the greater the pressure. Under certain circumstances the pressure increase can amount to as much as 3 cm. of mercury.

Professor Kunz (9), by theoretical considerations, has shown that this increase in pressure should be exactly proportional to the corona current.

Other investigators (10) have contended that the pressure increase could be completely accounted for as the result of Joule's heat and that the assumption that it is due to ionization is untenable. To support this contention Arnold performed experiments "by electrically heating the central wire in apparatus similar to Farwell's" and observed the pressure increase. With such an apparatus Arnold attempted to show: (1) that an increase in pressure due to heat ap-

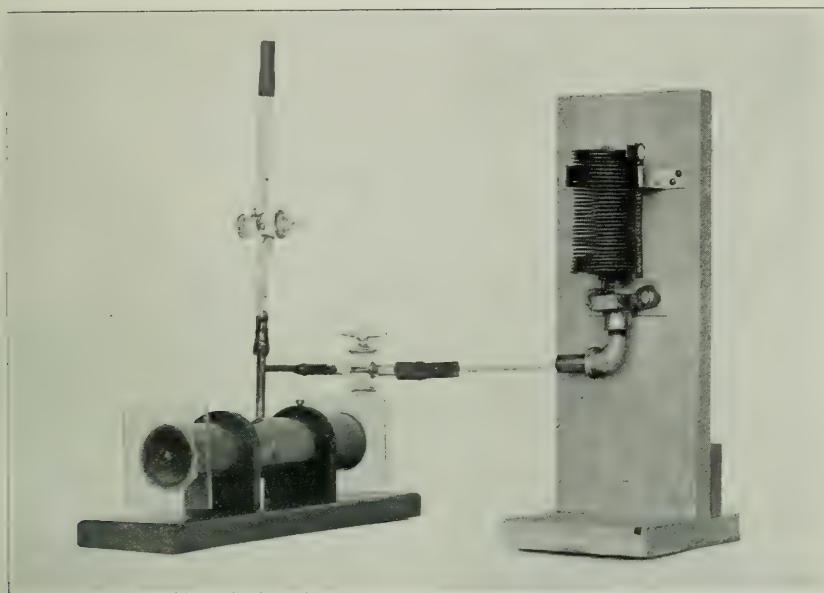


FIG. 36. APPARATUS FOR STUDY OF THE PRESSURE INCREASE IN THE CORONA TUBE

pears suddenly, and (2) that for a given power consumed in the tube the increase in pressure due to heat is of nearly "the same magnitude as those observed" in the corona.

In order to show clearly that the pressure increase is not due to heat a series of comparative experiments was performed with the pressure increase, caused (1) by producing the corona glow on the wire, and (2) by heating the central wire. The pressure increase observed in the first set of experiments will be referred to as *caused by corona* and in the second set as *caused by heat*. A few computations have also been made which strengthen the results of these experiments.

Since the conception of ionization is so intimately associated with the idea of increase in pressure, it seemed important to determine the laws relating to this sudden increase in pressure to the corona current.

24. *Apparatus.*—To the corona tube was soldered a small *T* tube, one side of which was joined to the vacuum pump and the other side was connected to a Bristol aneroid pressure gage (see Fig. 36).

The increase in pressure was measured by this Bristol gage. Any increase in pressure caused it to bend slightly and to rotate the mirror. When the deflection of a beam of light was seen over a scale,

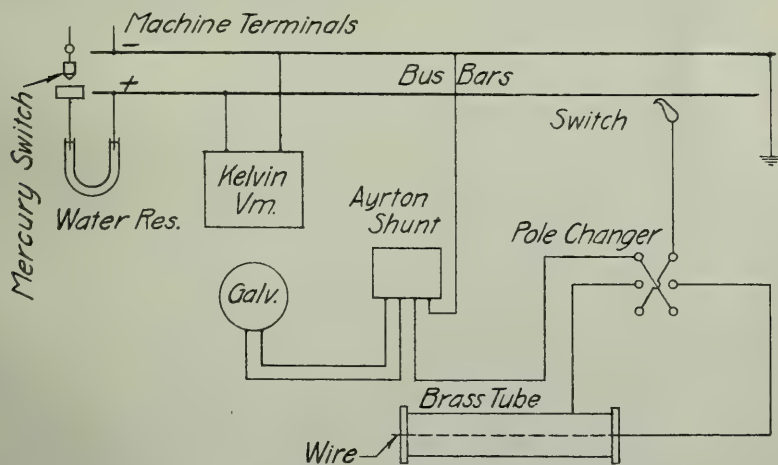


FIG. 37. DIAGRAM OF CONNECTIONS OF APPARATUS FOR THE DETERMINATION OF PRESSURE INCREASE IN THE CORONA TUBE

which had previously been calibrated by reading simultaneously the deflected beam and a water manometer connected directly to the gage, the increase in pressure in centimeters of water could be determined. The advantage of such a pressure measuring instrument in this experiment is its very quick action. The instant the pressure increases the gage jumps to its new position and a reading may be taken in a very few seconds. It was necessary to read this pressure increase quickly, because if much time was required the heating effect of the current would increase the pressure.

The current was measured by a Type *H* d'Arsonval galvanometer. The apparatus was connected as is shown in Fig. 37.

25. *Experimental Results.*—The results obtained from pressure increase in the corona were as follows:

(1) One who sees this pressure increase as recorded by a quick-acting pressure meter thinks it is not a heat effect, because of the rapidity with which it appears and disappears. Arnold showed that the pressure increase occurred very rapidly when caused by heat. The following curves show the difference in the rapidity in appear-

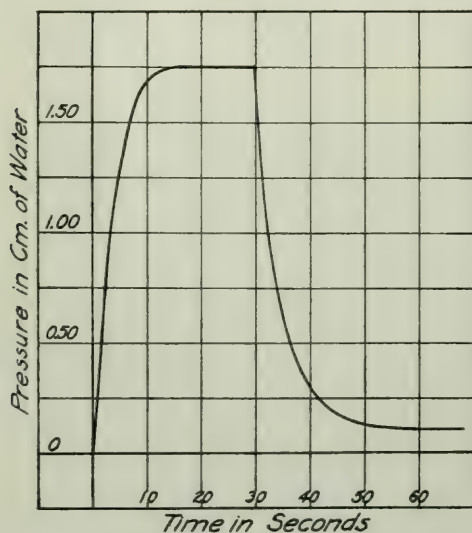


FIG. 38. PRESSURE INCREASE DUE TO HEAT

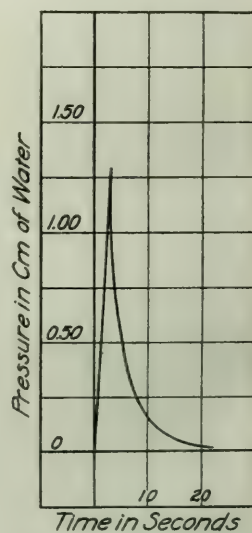


FIG. 39. PRESSURE INCREASE DUE TO CORONA

ance and disappearance of the pressure increase caused by heat and that caused by corona. It will be noticed in Fig. 38, where the pressure increase was caused by heating the central wire, that fifteen seconds were required for the pressure to come to its maximum value, and that from the time the current was broken twenty-five seconds were required for the pressure to return to practically its original value. In Fig. 39, however, where the pressure increase was caused by corona, only three seconds were required for the maximum pressure to be attained and the pressure came to practically its original value in eighteen seconds. In this last case from the appearance of the phenomenon, it seems, if the aneroid pressure meter had less inertia, that the pressure increase could be determined in less than three seconds. These curves show that the pressure increase appears five times as rapidly when caused by corona as when caused by heat and disappears also more rapidly.

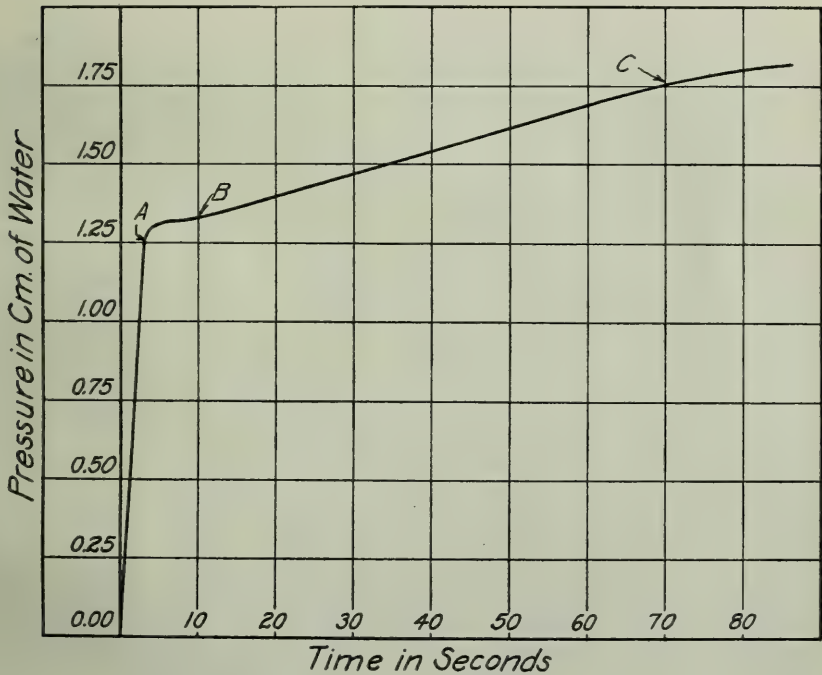


FIG. 40. PRESSURE INCREASE DUE TO CORONA AND HEAT

(2) In the pressure increase due to corona, a short time interval of five to seven seconds occurs after the sudden increase of pressure, before the heat effect in the corona begins to be noticed. This fact is shown in Fig. 40 by an abrupt bend, *a*, in the curve where the pressure increase is plotted against time. No such bend occurs where the pressure increase is caused by heat alone, as is shown in Fig. 38. In all the subsequent work the pressure increase measurements were always taken at a time corresponding to the point, *a*; by this means the heat effect is practically eliminated.

(3) The heat which is produced in the corona discharge, shown by the gradual pressure increase from *b* to *c*, Fig. 40, is distributed throughout the whole volume of enclosed air; consequently, when the circuit is broken, this heat does not radiate rapidly because the air is a poor conductor. This fact is shown very clearly in Fig. 41. The curve seems to show that the pressure increase due to heat in the corona is represented by the difference of ordinates of *c* and *b*, (Fig. 41). As soon as the circuit is broken at *c*, the increase in pressure due to corona at once disappears, but the increase in pressure due to heat in the corona discharge remains as is shown by the dif-

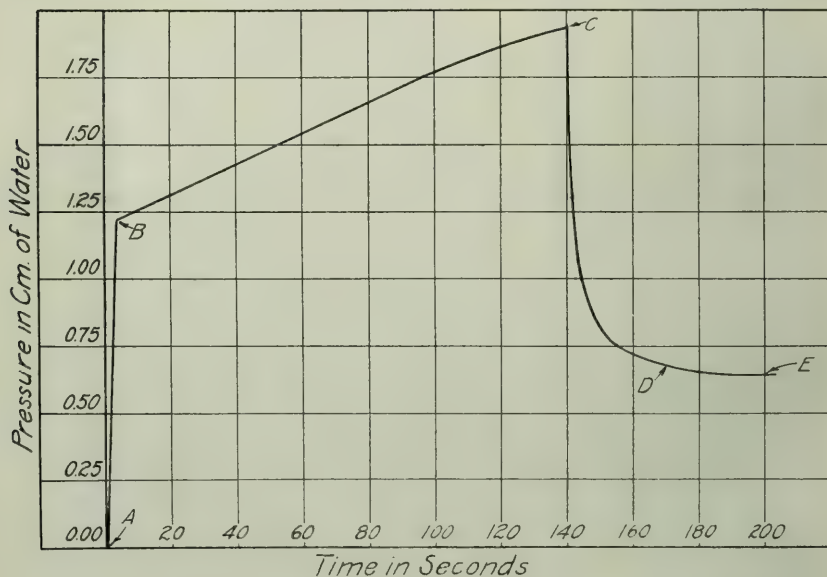


FIG. 41. PRESSURE INCREASE DUE TO CORONA AND HEAT

ference between ordinates d and a . This difference is always very nearly equal to the difference of ordinates of c and b . This heat energy produced by the corona current, since it is distributed through the gas, radiates very slowly, as is shown by the gradual descent of the curve from d to e . No such effect is observed when the increase of pressure is due entirely to heat, as is shown in Fig. 38. This curve shows that twenty-five seconds after the corona is removed from the wire the increase in pressure due to the corona has disappeared, but practically all the pressure increase due to heat in the corona (ordinate c minus ordinate b approximately equals ordinate d minus ordinate a) still remains and radiates very slowly.

(4) If the increase in pressure is due to heat, the same increase in pressure should result when the same power is consumed: (a) with a corona current through the gas and (b) with a heating current through the wire. Figs. 42 and 43 show that this is not the case. The powers consumed in the two cases are not exactly the same, but one can see that were they the same, the increase in pressure due to corona would be approximately half the increase in pressure due to heat. The power in the corona was obtained by multiplying the potential difference between the wire and the tube by the corona current, and in the heated wire the power was obtained by multiplying the current

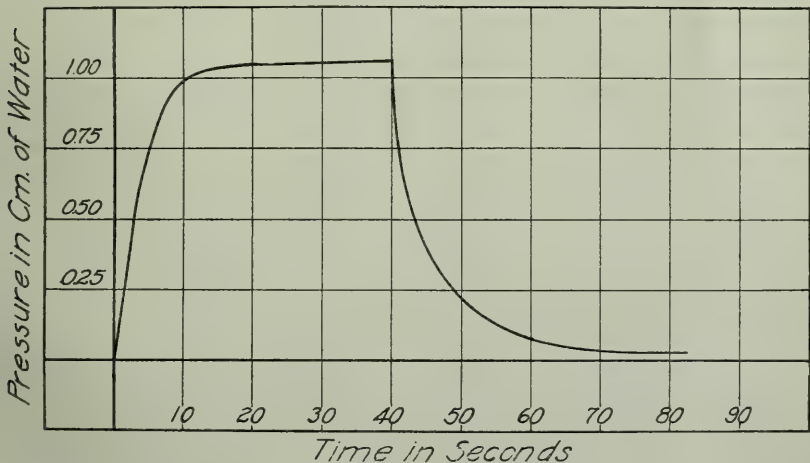


FIG. 42. PRESSURE INCREASE DUE TO HEAT. WATTS CONSUMED 0.238

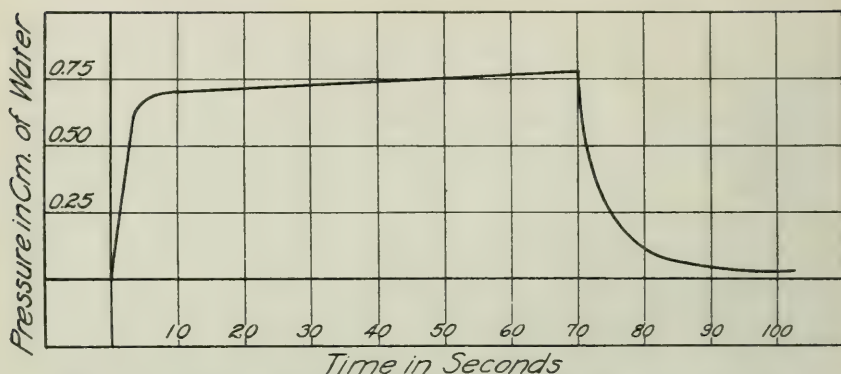


FIG. 43. PRESSURE INCREASE DUE TO CORONA. WATTS CONSUMED 0.266

through the wire by the potential difference across that portion of the wire which was in the tube.

(5) If the increase in pressure in the corona discharge is due to heat, the temperature of the air in the corona tube must increase. This condition may or may not be that of the luminous layer near the wire, but the temperature of the gas in the tube at a point four millimeters from the wire actually decreases. This decrease was determined by inserting a sensitive thermocouple made of very fine Copper-Advance wire into the corona tube. The temperature decreased only at the instant the corona appeared. In a short time after the heat due to the corona began to appear (corresponding to the slope b to c , Figs. 40 and 41) the temperature of the gas in the tube began to increase. This cooling effect is shown in Fig. 44. From a comparison of Fig. 44 with Fig. 40 it is seen that the increase in pressure which was measured at a was observed while there was an actual cooling in the corona tube. This cooling should be expected when air or oxygen is in the tube, for under these conditions ozone is formed. Since the formation of ozone from oxygen is always accompanied by an absorption of heat, the temperature of the air or oxygen would tend to lower. J. W. Davis, working on corona about hot wires in hydrogen, discovered that the appearance of the corona about a tungsten wire at white heat causes it to cool to dull red. This change tends to show that even in the corona glow itself there is a cooling effect. A possible explanation of the cooling effect might be given by assuming an electrical wind action around the conductor.

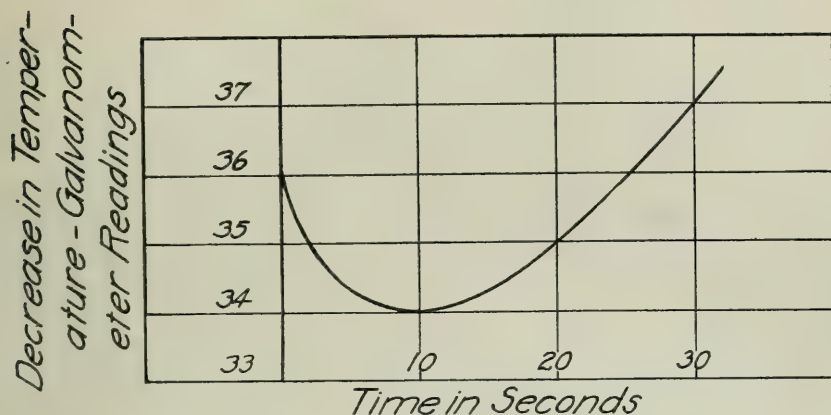


FIG. 44. COOLING EFFECT IN CORONA

(6) If the increase in pressure in the corona is due to heat, one should expect it to be the same with the wire either positive or negative. It will be mentioned hereinafter that it is impossible to obtain measurements when the wire is negative because of the presence of beads. The negative corona is entirely different from the positive corona.

(7) The following consideration will show, moreover, that the increase in pressure cannot be due to heat. The heat produced by the corona current will be given by the equation $H = 0.238 eit$, and if the observed pressure increase is due to heat, the increase in pressure

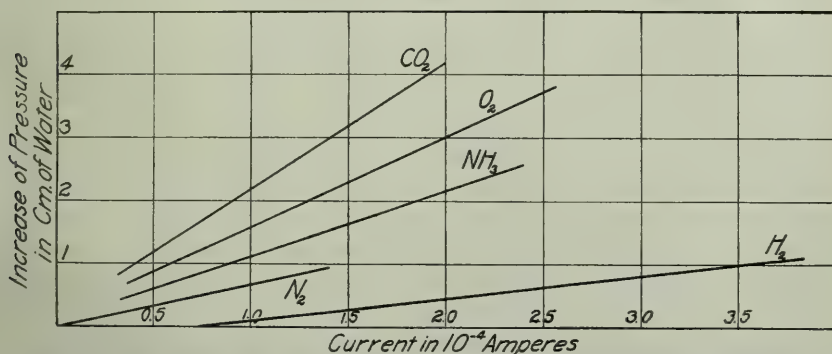


FIG. 45. RELATION BETWEEN IONIZATION PRESSURE AND CORONA CURRENT FOR DIFFERENT GASES

Δp will be proportional to the heat. The equation may then be written $\Delta p = k eit$. The only way for Δp to vary directly as i , the corona current, as shown by curves in the next paragraph, is for e to be independent of i . Data shows that this is not the case.

(8) To determine the laws relating this ionization pressure to the corona current, experiments were made when the wire was positive and the coaxial cylinder grounded with dry air, hydrogen, nitrogen, carbon dioxide, oxygen, and ammonia as the gases in the tubes. Considerable care was taken to see that these gases were absolutely pure. They were all dried carefully before they were used. Fig. 45 shows all the curves plotted to the same scale. With this scale the hydrogen curve should be continued until its ordinate is equal to that of the carbon dioxide curve.

The fact that the points all lie accurately on a straight line shows conclusively that the experiment verifies the prediction made by Dr. Kunz's theory. The law can then be stated that in the gases studied with the wire positive *the ionization pressure is exactly proportional to the corona current.*

In oxygen a considerable amount of ozone was formed because of the corona discharge. Evidently the curve as shown is a resultant of two effects: (1) A chemical change, due to the formation of ozone, which would tend to cause a decrease in pressure. (2) The increase in pressure due to the ionization of the oxygen. Since the ionization curve is a straight line, as is shown by the gases in which probably there is no chemical action, and since this resultant curve of oxygen is a straight line, the following law can be stated:

Whenever chemical change occurs because of the corona the chemical change is proportional to the current.

With the wire negative beads always appear, and since the pressure increase varies with the arrangement of the beads which are not stable, it is impossible to verify accurately the relationship. When an ordinary open manometer which is slow in its action was used instead of the quick acting gage, it was discovered that the same relationship as stated is very nearly true for the negative as well as for the positive wire.

The increase in pressure in nitrogen, showing ionization, is one of the exceptions where nitrogen is largely ionized at low temperatures and thus probably chemically active. How nitrogen, carbon

dioxide, and ammonia are ionized are questions which require further study.

The arrangement of the apparatus could be used as a high potential voltmeter by simply calibrating the increase in pressure against volts, as determined by a disc electrometer.

26. *Results from Theoretical Considerations.*—If the increase in pressure is due to heat, it is possible to compute the magnitude of the pressure increase when one knows the watts of electrical energy consumed in the tube. The trial represented in Fig. 43 gives these data. The observed pressure increase was measured in three seconds so that the total number of joules of work consumed by the tube in that time was $3 \times 0.266 = 0.798$ joules. This amount corresponds to 0.1909 calories. Knowing the volume of the tube, the temperature and pressure of the air in it, one can readily compute the mass of the air in the tube. With the quantity of heat and mass of air mentioned previously, together with the specific heat of the air at constant volume, the temperature rise of the air can be computed, if the electrical energy is assumed to be converted into heat. This temperature rise is 2.44 degrees centigrade, which at constant volume corresponds to a pressure increase of nearly nine centimeters of water, while the observed pressure increase in this particular trial amounts to nearly seven-tenths centimeters of water. In this computation radiation and conduction losses have been neglected, because they would be very small from a body 2.44 degrees centigrade above room temperature. This computation shows that the observed results lie in a different order of magnitude from that expected if Arnold's theory were true.

Arnold states, if "we compute the corona currents that would result from the presence of enough ionized particles to produce the observed pressure changes, the currents calculated are many thousand times greater than those actually obtained." Such a statement is true only when the ionized particles are produced in a uniform or practically uniform electric field. This is not the case in the corona tube, as is shown in Chapter VII.

From these data it is seen that the potential gradient near the wire is very high, of the order of 30,000 volts per centimeter. This is the arcing gradient, in which probably every molecule is ionized. Then for a long space between the wire and the tube there is a very small gradient. With this condition of the field, every molecule may

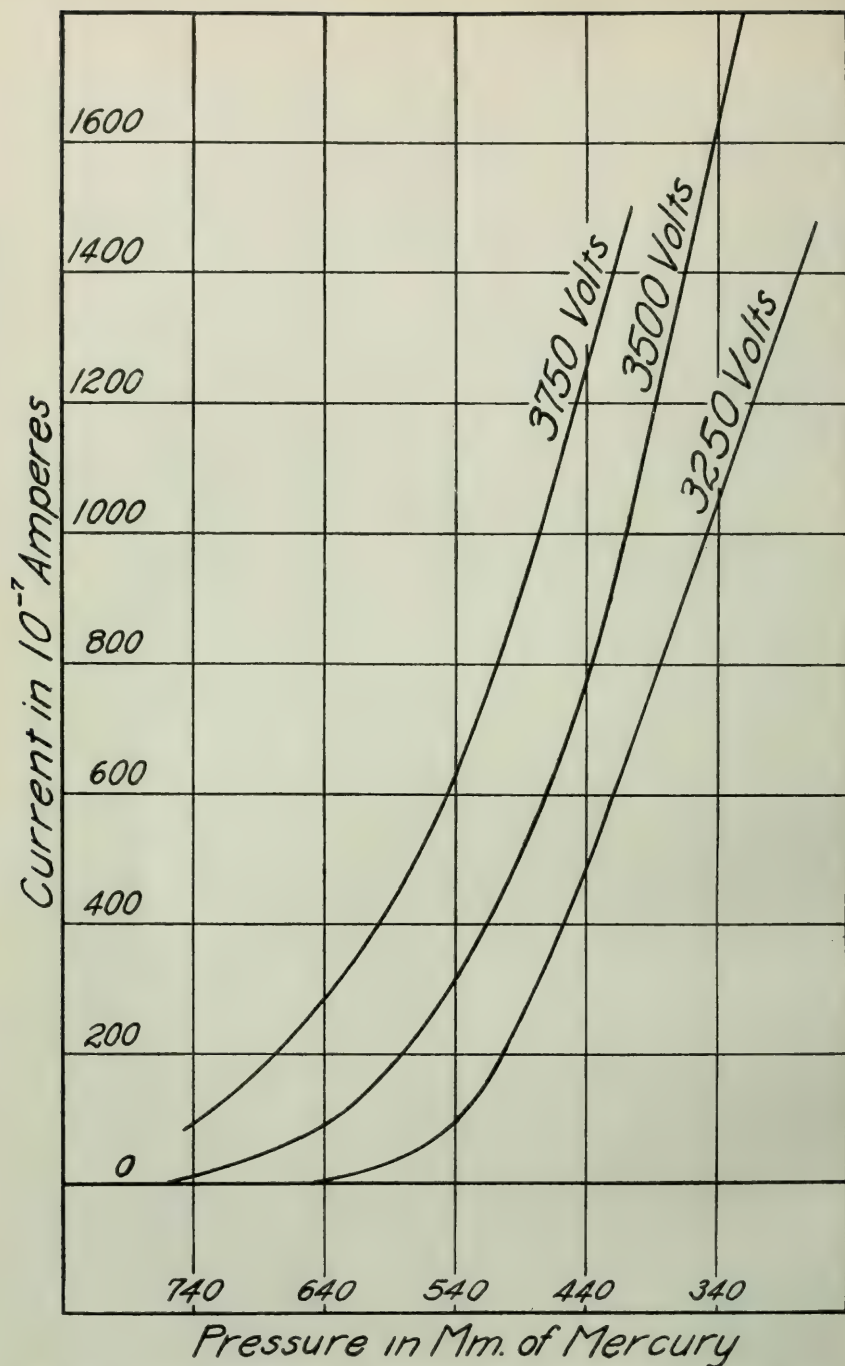


FIG. 46. CORONA CURRENT AS A FUNCTION OF PRESSURE IN HYDROGEN, WITH CONSTANT VOLTAGE AND WIRE POSITIVE

be ionized near the wire and still the resultant current be very small, for few of the ionized particles near the wire will pass through the space where there is a small gradient. Simple computations based on kinetic theory show that the maximum observed pressure increases can be explained by ionization if every molecule of the air within 1.39 millimeters of the wire is ionized. Within this distance the potential gradient is equal to the arcing gradient and it is therefore probable that all molecules are ionized.

27. *Further Verification of Kunz's Theory.*—The final equation as presented by Dr. Kunz is $ki = \frac{v_0}{e} (p_1 - p_0) \frac{1}{t} + \text{a constant}$, where

i is the corona current, v_0 , the volume of the tube, e , the potential difference between the wire and the tube, $p_1 - p_0$, the pressure increase, k , a constant and p_0 , the initial pressure. This equation shows that for a constant potential difference, e , the current, i , should increase as p_0 is lowered. Data were taken by measuring the current at various measured pressures, caused by a constant potential difference, which verifies this theory. These data are shown graphically in Figs. 46 and 47 when pure hydrogen and nitrogen respectively were the gases in the tube.

28. *Summary and Conclusions.*—Experimental results show:

(1) That the increase in pressure due to the corona appears and disappears much more rapidly than when due to heat only.

(2) That the heat in the corona discharge is not a prominent factor until many seconds after the corona appears.

(3) That in equal energy experiments the increase in pressure due to corona differs from the increase in pressure due to heat by nearly 50 per cent.

(4) That at the instant the corona appears the gas in the tube at a small distance from the wire is cooled.

(5) The ionization pressure in the positive corona is exactly proportional to the corona current in dry air, hydrogen, nitrogen, carbon dioxide, oxygen, and ammonia.

(6) Any chemical action that occurs because of the corona is proportional to the corona current.

(7) That the theory advanced by Professor Kunz is verified in one more field; namely, in the relation between current and pressure for constant voltage.

These results together with conclusions drawn from simple calculations force one to believe that the pressure increase in the corona

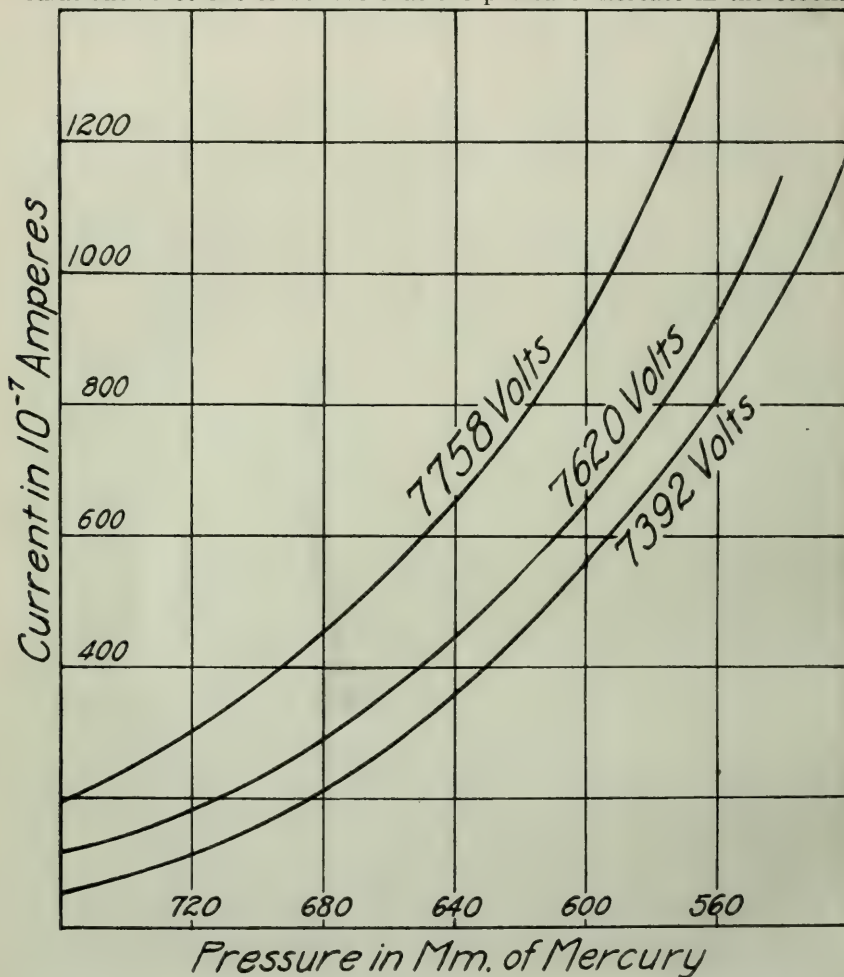


FIG. 47. CORONA CURRENT AS A FUNCTION OF PRESSURE IN NITROGEN, WITH CONSTANT VOLTAGE AND WIRE POSITIVE

discharge is not due to Joule's heat. With the knowledge of the distortion of the field in the corona tube it seems very possible that the increase in pressure is due to ionization.

Dr. A. M. Tyndall has also argued against a characteristic pressure effect in the corona. In his experiments he used a much smaller tube and introduced about one thousand times more energy per unit time than that used in these experiments, unless there is a misprint in the current (10^{-6} instead of 10^{-3}). Even if there were a misprint, the relative energy is still larger in Tyndall's experiments, because his inner wire was about thirty times smaller than those used in the measurements herein recorded. It is therefore possible that Tyndall observed only heat phenomena; moreover from his data it cannot be concluded that the pressure increase in question is proportional to the corona current, a fact which requires an explanation different from a simple heat effect. The cooling of the wire by the corona had been discovered in the Physics Laboratory of the University of Illinois before Tyndall published his paper. Tyndall's experiments cannot be considered conclusive; the characteristic pressure measured by Warner may be due to an increase in particles or to a partial vacuum surrounding the wire when the corona discharge takes place. The problem is not yet solved.

CHAPTER IX

OZONE FORMATION IN THE CORONA

Among the problems attracting attention at the present time, that of the nature of the forces which hold the atoms together in the molecule is of great importance. The most probable suggestion is that these forces are due to the electrons and positive nuclei of the different atoms acting on each other according to laws still obscure. Most of the articles which have been published concerning this problem are of a speculative nature. If the forces are electrical, it seems obvious that some electrical method might be used advantageously in their study. Ionization, often followed by chemical reaction, is found to occur in solutions of electrolytes and sometimes in gases. A tremendous amount of work has been done with electrolytes in solutions of various solvents. These studies have led to the development of many interesting relationships, but there are so many complications in any study of liquid solutions that it is difficult to get much conception of the fundamental intramolecular forces. In spite of the fact that a much greater amount of work has been done on ions in solutions than on gaseous ions, more is known about the latter. In gases the ions have greater freedom of movement than in liquids. The structure is simpler and it is much easier to control and alter conditions. Ionized gases with charged atoms and molecules are often capable of causing chemical action and so may well lend themselves to the study of those forces which bind the atoms together. To cause a reversible reaction like $\text{N}_2 + \text{O}_2 \rightleftharpoons 2\text{NO}$, for instance, to shift toward the right by purely thermal means would require a very high temperature for appreciable yields, but with the ionization of gases resulting from various forms of electrical discharge, similar yields can be secured at far lower temperatures. It seems probable, then, that the presence of ions in gases is the cause of new combinations of the atoms, but it might be that ionization is only an accompanying effect, not the cause of chemical reactions. It is very desirable when studying fundamental relationships to work with conditions as little complicated as possible. For this purpose there is available one re-

action that involves the presence of only one element, oxygen, which is changed into ozone under suitable conditions.

The following is a discussion of the theory of ozone formation which is applied to the various known types of ozone formation: the oxygen atom is supposed to possess six electrons in the outer shell. The two atoms in the molecule may be held together in two different ways, between which there may be several gradations. The oxygen molecule may be represented by either of the formulas A, $:\ddot{\text{O}}: \ddot{\text{O}}:$ or B, $:\ddot{\text{O}}:\ddot{\text{O}}:$. In the first form the atoms are held together by two valence bonds while in the second there is only one bond, each atom possessing an extra, unsatisfied valence. It is supposed that a valence bond is due to the coupling together of two electrons which tend to make a fairly stable union. In form B each atom has an extra unbalanced electron, and an arrangement exists similar to the usual conception of the ethylene molecule. In its second form the oxygen molecule would be highly reactive as, indeed, oxygen is well known to be.

If a neutral oxygen atom came in contact with form B, there would be a strong tendency to form the neutral molecule of ozone,

$:\ddot{\text{O}}:\ddot{\text{O}}:$
 $:\text{O}:$ The electrons not being symmetrically placed about the

nuclei a strain results so that ozone is in an unstable condition and readily tends to decompose. The heat of decomposition of ozone by direct measurement is about +34,000 calories. This value is the resultant of the force required to split two extra atoms from two ozone molecules and of the force with which these two atoms unite to form a molecule, regardless of the order in which these steps may occur. It seems likely that an atom would have to come in contact with the unsaturated form of molecule B at just the right angle and with a suitable velocity in order to produce ozone. Collision between two atoms would result in the formation of a molecule with consequent degradation of energy as heat.

Apparently the formation of ozone requires oxygen atoms which may be derived from molecular oxygen or from some compound of oxygen with other elements. On this basis, in accordance with the mass-action principle, any factor which increases the atomic oxygen concentration ought to raise the yield of ozone.

Ozone is formed in many chemical reactions. The practical

method for the manufacture of ozone is to pass air through some form of silent discharge. Whenever ozone is formed by means of an electrical discharge, light is produced. Indeed ultraviolet light of sufficiently short wave length produces ozone. It is possible that it is the light which produces the ozone even in the silent discharge and in the corona discharge. The vibrations of the ultraviolet light tend to loosen the oxygen bonds, to produce polarization at first and finally to cause dissociation of the atoms analogous to the thermol action of high temperatures.

The formation of ozone is an end of thermic reaction. At ordinary temperature ozone decomposes into oxygen, but the rate of decomposition is slow. The velocity of decomposition increases very rapidly with increasing temperature, so that for practical manufacture of ozone the gas should be as cold as possible.

For the formaton of ozone atomic oxygen seems to be required; the atoms may or may not be changed and this is a very important question.

The chemical reaction may be written in the form $O_2 - O \rightleftharpoons O_3$. The heat of decomposition of ozone is about 34,000 calories. Ozone is, therefore, in a metastable condition at ordinary temperatures.

For the ozone formation in the corona discharge the following method and arrangement were chosen. The oxygen was prepared by electrolyzing a 20 per cent solution of sodium hydroxide with nickel electrodes. To remove hydrogen the gas was passed over heated copper oxide. Any carbon dioxide was removed by a 20 per cent sodium hydroxide solution in a bead tower. The gas was dried

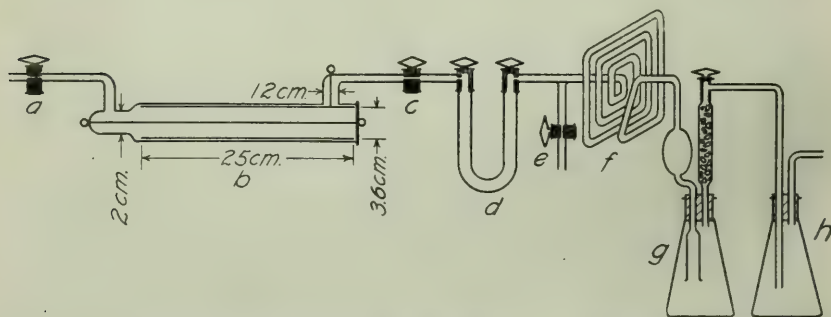


FIG. 48. DIAGRAM OF APPARATUS FOR THE STUDY OF OZONE FORMATION IN THE CORONA

by being passed through another bead tower containing concentrated sulphuric acid, through a large U tube filled with pieces of fused potassium hydroxide and finally through another large U tube full of phosphorous pentoxide. The corona tube was of glass; its dimensions are given in Fig. 48. The outer electrode was a sheet of gold foil 0.15 mm. thick. Connection was made by a platinum wire sealed through the glass and passing all around between the foil and the glass tube. A slit was left in the foil so that the discharge might be observed. It had the characteristic appearance for this form of discharge as described previously in this bulletin. The procedure was to fill the tube with pure oxygen, close the stopcocks and subject the enclosed volume of air to the discharge for varying lengths of time. The gas was then passed through neutral 2 *N* potassium iodide. The iodine set free was titrated with 0.025 *N* thiosulphate solution after acidifying with sulphuric acid. During the discharge the current strength was measured by a suitable galvanometer and was main-

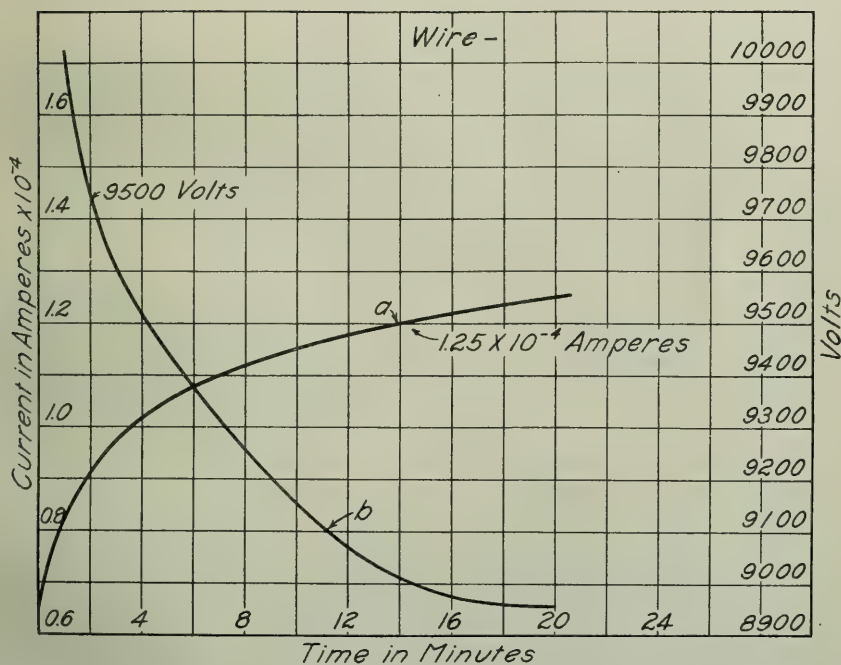


FIG. 49. INCREASE OF VOLTAGE AT CONSTANT CURRENT AND DECREASE OF CURRENT AT CONSTANT VOLTAGE IN THE FORMATION OF OZONE IN THE CORONA

tained constant by increasing the voltage as required. The resistance of the gas rises with the length of time of the discharge. The required increase in voltage due to the increased resistance is an exponential function of the time

$$V_t = V_0 e^{at}$$

V_0 is the initial voltage, V_t is the voltage at any time t , and a is some constant. This relation is well illustrated in Fig. 49, curve a . On the other hand if the voltage is maintained constant, the current strength will decrease as in Fig. 49, curve b . The formula for this hyperbolic curve will be somewhat like the other formula but with a negative exponent. An explanation of this phenomenon is given later. The state of affairs in the discharge is somewhat complicated. When the current is turned on, there is a slight immediate rise in pressure due to the ionization of the gas. This increase in pressure means a splitting of the molecules into atoms so that the total number of particles in the gas is increased. The oxygen atoms formed in oxygen unite chiefly with oxygen molecules to form oxone with a consequent decrease in volume which may be followed by a suitable manometer. The most (90-97 per cent) of even the initial energy is degraded into heat energy. As the ozone increases in concentration more of it decomposes with the liberation of more heat. All this heat causes an increase in the velocity of the molecules and an increase in the volume of the gas. The decrease in volume, which is a resultant of the ozone and heating effects, should bring about a decrease in resistance. The increased velocity of the molecules should also help to lower the resistance. Both of these effects should allow the easier passage of the ions through the gas. The explanation of the increase in the resistance is the counter electromotive force or polari-

TABLE 5
CURRENT-VOLTAGE RELATIONSHIP

Wire Positive		Wire Negative	
Amperes $\times 10^{-4}$	Volts	Amperes $\times 10^{-4}$	Volts
2.00	7910-8300	1.25	8960-9550 ¹
2.77	8960-9260	2.50	9880-10280
3.75	9370-9650	3.75	10400-10600
6.25	9680-10440	5.00	10800-11240
		7.50	11600-12480

¹ Cf. Fig. 49, Curve a

zation effect exerted by the ions present. As long as the tube is closed its size is the limiting factor. After a condition of equilibrium is once reached throughout the tube, the voltage required to maintain a certain amperage should be constant. The ionic equilibrium like the ozone-oxygen equilibrium depends upon diffusion to a large extent and this in turn is governed by the size and shape of the tube.

These data are the extreme values observed during a 20-minute run. To test the reproducibility of the method, runs were made during two different days with all the conditions as nearly constant as possible. Each run lasted just three minutes. The current strength was maintained exactly at 2.77×10^{-4} amperes and the wire was posi-

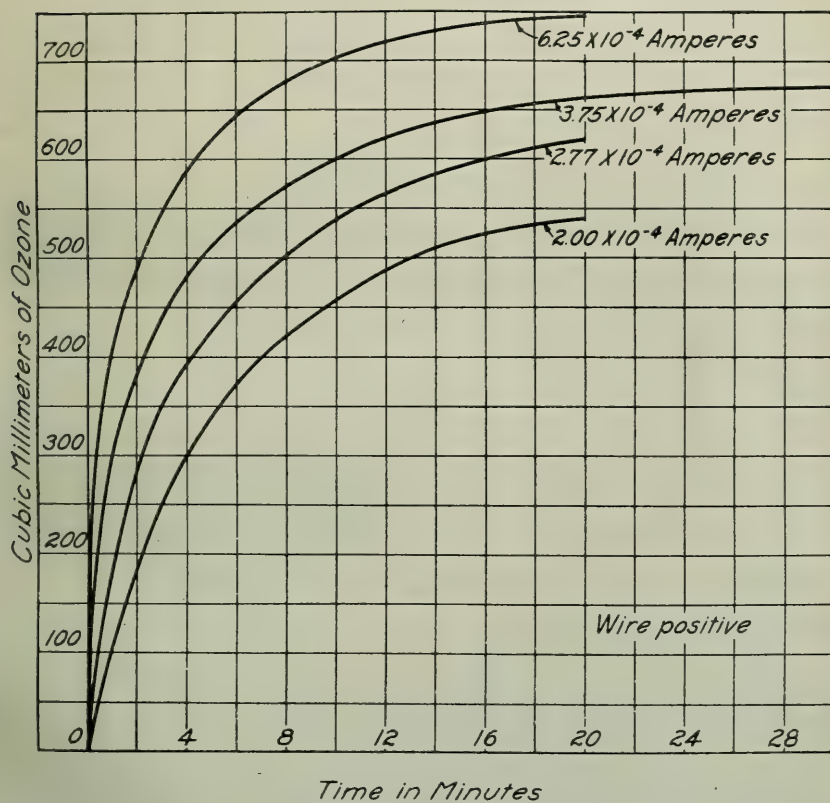


FIG. 50. OZONE FORMATION IN THE CORONA TUBE AT VARIOUS CURRENT STRENGTHS WITH WIRE POSITIVE

tively charged. The results were 345, 340, 335, and 360 cu. mm. of ozone. This corresponds to nearly 6 g. per kw. hr., a value lower than the values given hereinafter; for here the deozonizing effect of the discharge is considerable. To calculate the yield in terms of percentage divide the value in terms of cubic millimeters by 3000.* The results plotted in Figs. 50 and 51 represent all the results obtained with the amperage at a constant value and with no arc in series. The following yields have been calculated from measurements of the initial slopes of these curves.

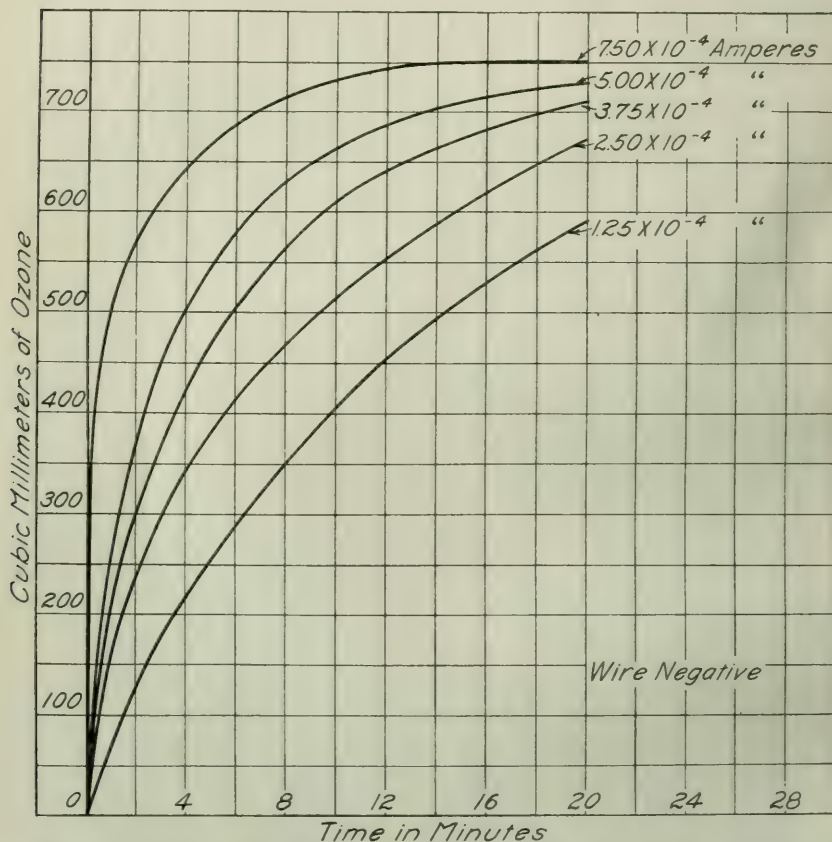


FIG. 51. OZONE FORMATION IN THE CORONA TUBE AT VARIOUS CURRENT STRENGTHS WITH WIRE NEGATIVE

* The capacity of the tube being 300 cc. to change from cubic millimeters to percentage multiply by 100 (300×1000) or divide by 3000.

TABLE 6

OZONE YIELDS CALCULATED FROM THE INITIAL SLOPES OF THE CURVES
IN FIGS. 50 AND 51

Wire Positive Grams of Ozone per Kilowatt Hour			Wire Negative Grams of Ozone per Kilowatt Hour		
Amp. $\times 10^{-4}$	Without Spark	With Spark	Amp. $\times 10^{-4}$	Without Spark	With Spark
2.00	7.7	13	1.25	13	22
2.77	12.7	18	2.50	14.1	23
3.75	20.7	29	3.75	14.2	25
6.25	23.3	..	5.00	11.3	..
....	....	..	7.50	24	..

These values are being checked by passing the gas through the discharge at various speeds. With the wire charged positively, about the same amount of ozone is formed as with the wire charged negatively. This result does not agree with either Warburg* or Cermak† who working with a point discharge and influence machine current observed the ozone concentration with the point negative to be about three times the concentration when the point was charged positively. Their explanation was that the greater speed of the negative ions was responsible. This seems to be a reasonable explanation, but these curves show that there is something more to be taken into consideration. The point discharge, especially with an influence machine supplying the current, is very complicated. The curves in Figs. 50 and 51 belong to a family of parabolic curves which tend to approach a common point as a limit. The general formula for these curves is,

$$y = a t^n$$

where y is the yield of ozone, a is a constant, t is the time, and n is a fraction between 0 and 1. The greater initial slope of the larger current curves indicates that there is a greater ozonization, but the smaller slopes of these curves after five minutes show that there is also a very much larger deozonizing effect. The resultant is probably the same in all cases with an electrical equilibrium formed. This electrical equilibrium for any one apparatus and source of power is probably independent of the current strength. It is the resultant of the ozonizing and deozonizing effects of the current and the small spontaneous decomposition of ozone at the temperatures (24 ± 3 degrees) and pressures (740 ± 5 mm.) used.

* Ann. Phys., Vol. [4] 9, p. 781, 1902.

† Ber. deut. physik. Ges., Vol. 4, p. 268, 1906.

A few experiments were made with a spark gap in series. The spark was between two 1 cm. zinc spheres which were adjusted by a micrometer screw. The effect of an arc in series with the corona has been studied by Crooker.* He showed that the effect is not to produce an oscillating but an intermittent direct current. In Table 6 some yields are given of ozone per kilowatt hour. These were calculated as follows: With the wire positive and with the current of 2.00×10^{-4} ampere, the yield of ozone was two-thirds greater for the three-minute interval with rather than without the spark in series. The increases are greater for the smaller current strengths. These results throw some light on the effect of alternating or fluctuating current and of different frequencies on ozone production. This point will be discussed later in connection with the further study of ozone formation in the corona which is being continued in the Chemical Laboratory of Purdue University.

*Crooker, Am. J. Sci., Vol. 45, p. 281, 1918.

CHAPTER X

THE INFLUENCE OF A SERIES SPARK ON THE CORONA

The typical positive corona discharge is a uniform glow around the wire, while the negative corona consists in more or less evenly spaced bright beads. If a short spark is included in series with the corona tube, this difference in the discharge is largely eliminated, the discharge appearing almost the same whether the wire is positive or negative. The introduction of the spark in series entirely changes the visual character of the corona glow. The usual characteristic negative beads spread laterally and in diameter into a fuzzy glow (blue in air), whereas the quiet uniform positive glow gives place to a remarkable display of purple streamers shooting radially from the wire to the tube and at times completely filling the tube with light. These visual characteristics are essentially the same in all gases.

When this marked difference between the corona with and without the spark in series was first discovered, it was suggested that perhaps this difference was due to high frequency oscillations super-

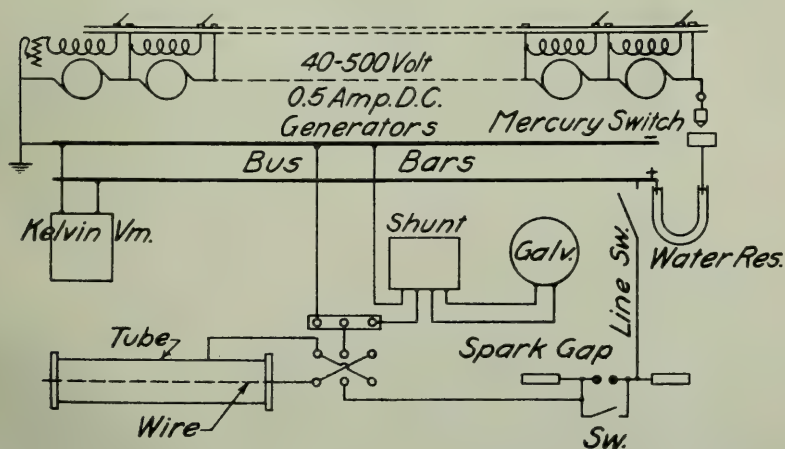


FIG. 52. DIAGRAM OF CONNECTIONS OF APPARATUS FOR STUDY OF INFLUENCE OF A SERIES SPARK ON THE CORONA

imposed upon the direct-current phenomenon. The results presented in the following pages of this chapter comprise the present knowledge of this peculiar corona phenomenon.

29. *Apparatus.*—The electrodes of the spark gap were polished brass spheres, one centimeter in diameter, fastened to brass rods which were supported by hard rubber blocks on a solid hard rubber base. One of the electrodes was supplied with a micrometer screw and an insulated handle which permitted an easy adjustment of the spark discharge. This spark gap was connected in series with the self-opening line switch and the corona tube through a reversing switch which allowed quick reversal of the polarity of the axial wire. The connections of the apparatus are shown in Fig. 52.

30. *Visual Characteristics of the Corona with Spark in Series.*—If in positive corona a short spark is placed in series with the corona tube, containing air at atmospheric pressure, after the voltage is high enough to give a bright uniform glow a most remarkable change takes place in the discharge. For very short sparks a few bright purple radial pencils or streamers of light will shoot out irregularly from the wire toward the tube. These streamers increase in number and in brightness as the spark gap is opened and may at times completely fill the tube with purple light. They are brighter and more easily formed at the higher pressures and at voltages slightly above that for the starting glow, but they have been observed at pressures as low as 30 cm. of mercury.

The same changes in the appearance of the positive glow by the introduction of a series spark have been observed in illuminating gas and hydrogen. The uniform positive glow is in both cases transformed into the radial streamers by the action of the spark. In illuminating gas these streamers are of an intense blue-green color, while in hydrogen they are of a milky white or silvery appearance.

In negative corona a short series spark has the effect of destroying the characteristic negative beads. Introducing a very short spark reduces the clear beads in brightness and in their clear-cut form, and they become hazy at the boundaries. Gradually opening the spark gap causes a slow transition of the beads from the clear intensely concentrated form of glow to a uniform fuzzy glow which spreads laterally from the beads along the wire and which is slightly larger

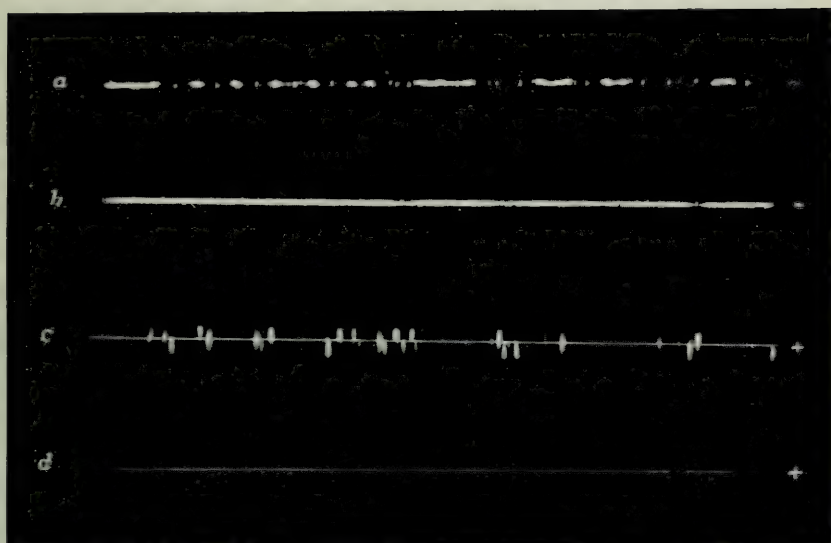


FIG. 53. CORONA DISCHARGE WITH AND WITHOUT A SERIES SPARK

in diameter than the original beads. The bright cores of the beads maintain their positions until the last, although they are greatly reduced in intensity and may even be seen when the spark gap is so long that the glow flashes but intermittently. The characteristic destruction of the clear form of the beads due to the action of the spark has also been observed in illuminating gas and in hydrogen at various pressures. The appearance of the glow remains the same, whether the spark is placed on the grounded side of the tube or on the high potential side.

Photographs of the corona discharge with and without a series spark are shown in Fig. 53.

31. *No Oscillations in the Corona.*—When the influence of the series spark was first discovered, the action was attributed to oscillations or surges started in the system by the spark. This suggestion was made, because when a 2 micro farad condenser was placed in parallel with the tube and the wire, the hazy, beaded discharge appeared for both positive and negative corona, and did not change in character when a series spark was added to the circuit. When the spark is placed in series many times, a hissing sound is heard which might be due to oscillations.

To determine whether the series spark sets up oscillation several experiments have been performed. The results, which show that oscillations are not present, will be given in the following paragraphs.

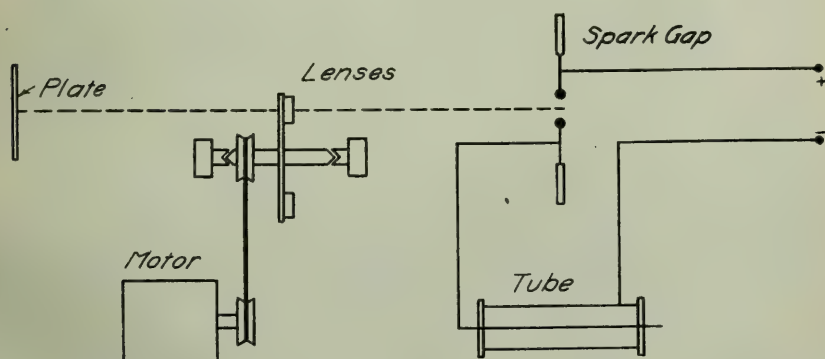


FIG. 54. ARRANGEMENT OF APPARATUS FOR BOYS'S METHOD

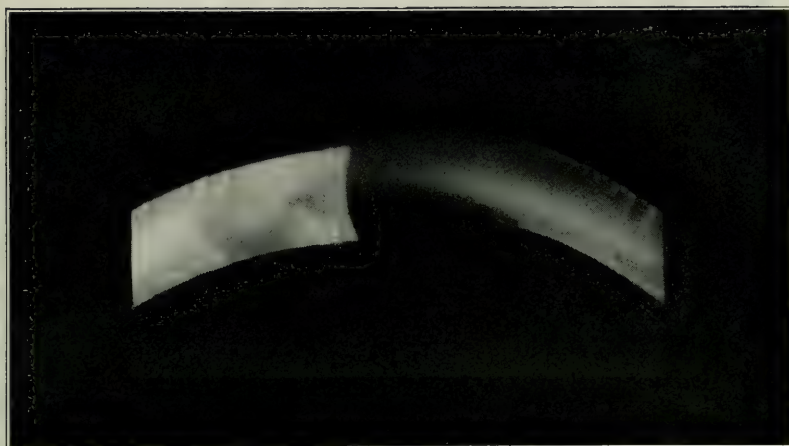
The difference between the positive and negative corona with series spark, as described, is so conspicuous as to exclude the possibility of the effect being due to oscillations. If there were oscillations, they could not be symmetrical with respect to the time axis.

The oscillograph and vibration galvanometer cannot be used to determine the current wave form, because the currents are too weak to overcome the inertia of the moving elements. Three methods have been used which give accordant results: the telephone, revolving lenses and a photographic plate, and a cathode tube with a hot lime cathode. The last method may be made very sensitive and gives satisfactory results.

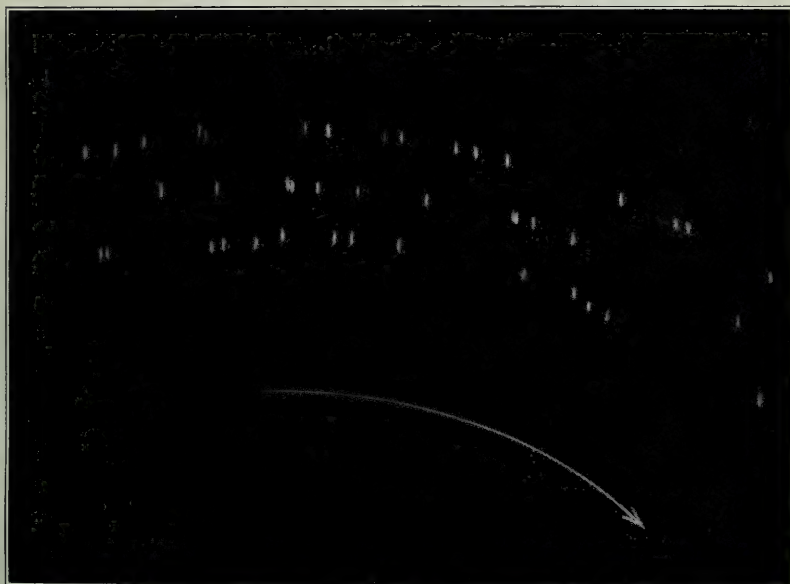
In the telephone receiver method a receiver connected in parallel with a resistance was used in place of the galvanometer. The passage of the faintest spark can be detected. When the voltage is high enough to produce corona, a sharp click is heard in the telephone as each consecutive spark passes and a flash of glow appears on the wire in the tube. If the sparks pass in very rapid succession, the glow will appear to be practically continuous. The discharge between the spheres is intermittent and forms a white line in the gas.

The corona tube acts like a condenser charging and discharging at intervals, according to the length of the spark gap. It can be arranged so that for long sparks only one spark passes per second or for short sparks several thousand pass per second, and as each spark passes it will register a sharp click in the telephone receiver. Decreasing the spark length from the longest sparking distance will make the sparks jump faster and faster until for very short spark lengths the sound in the telephone practically passes from the audible range. The results obtained with the telephone suggest the assumption that the corona current with a spark in series is only intermittent and not oscillatory.

Boys's method consists in photographing the spark directly when the image from it sweeps across a photographic plate. Boys (19) used a system of six revolving lenses set in one solid disc. Each lens was mounted a little offset from the center of the disc as compared with those adjacent, so that the image from it would not overlap the others. The arrangement of the apparatus is shown in Fig. 54. All the lenses have the same focal length; so the spark gap can be focused on the plate through any one of them. The spark gap and the photographic plate are stationary, but since the lenses move, the



a



b

FIG. 55. PHOTOGRAPHS OF OSCILLATORY AND UNIDIRECTIONAL SPARKS

focus of the spark shifts from one point to another across the plate leaving its record of instantaneous images.

A small motor drives the lenses at a speed of about 6000 r. p. m. The lenses are set about four inches from the center of the disc so that it is possible to get a linear speed of approximately 100 ft. per sec. across the face of the photographic plate.

By this method it is possible to analyze the spark and to determine whether it is of an oscillatory or unidirectional character. An oscillatory spark will give an irregular band of light across the plate (see Fig. 55A), while a unidirectional spark leaves only a sharp line (see lines in Fig. 55B).

For rough determinations it is easy to observe the image of the spark on the ground glass plate and to find quickly if the spark is oscillatory or not. If it is oscillatory, one can observe the approximate frequency and duration of the spark. For more nearly accurate determinations photographs must be made on sensitive plates and observations and measurements made from them.

Several observations were made with this method for various spark lengths and speed of lenses using both air and hydrogen in the corona tube. In the first experiment corona was produced in air at a pressure of 500 mm. by a potential of 14,000 volts. The spark gap was about 1.5 mm. in length and the lenses were driven at a speed of 2,000 r. p. m. A photograph was taken, but the individual sparks showed no trace of being oscillatory.

To spread out the individual spark images the lenses were driven at the higher speed of 6,000 r.p.m. and the spark gap set at 1.19 mm. This arrangement allowed a passage of nearly 2,500 sparks per second and a speed of about 100 ft. per sec. across the plate. The half-tone, Fig. 55B, clearly showed that the sparks were not of an oscillatory character but unidirectional, that only a sharp line was recorded as each spark passed, and that the duration was less than 1-100,000 second. Each spark was, moreover, a little brighter at the negative electrode, and showed that all the sparks passed in the same direction and were of the same character.

With hydrogen in the tube at a pressure of 744 mm. and a potential of 9,400 volts photographs were taken when the spark gap was 0.75 mm. and 0.3 mm in length. For the 0.75 mm. gap the frequency of the sparks was about 10 per second and produced a large number of silvery streamers in the corona tube. When the gap was

reduced to 0.3 mm., several hundred sparks passed per second and the corona tube was completely filled with streamers. In every case the sparks were unidirectional, sharp and clear-cut, and showed no oscillatory character whatever.

To determine the form of the current curves when the spark is in series a special hot-lime-cathode Braun tube was designed and constructed as shown in Fig. 56.

A narrow platinum strip, P , fastened to the insulated brass blocks, B_1B_2 , is heated by an auxiliary current passing through the leading-in conductors, C_1C_2 . A small spot of calcium oxide placed upon this heated strip has a peculiar property of giving off a stream

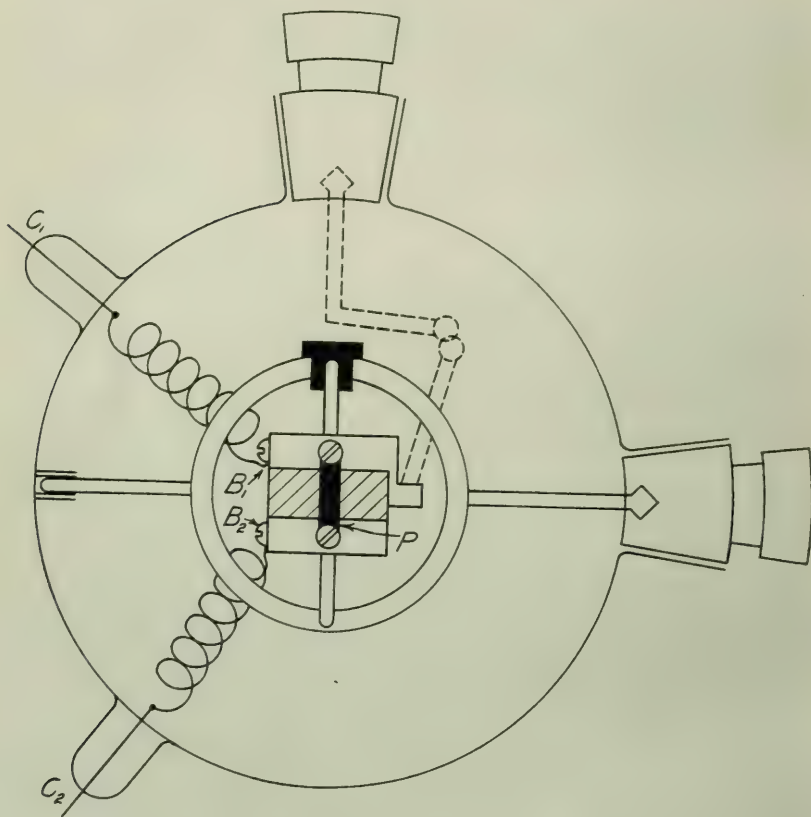


FIG. 56. THE ADJUSTABLE HOT-LIME CATHODE

of slow moving electrons when used as cathode in a discharge tube at a very low pressure. It is necessary to use only a low potential of nearly 400 volts between anode *A* and cathode *C*. The block holding the platinum strip was mounted upon a gimbal support, as shown, in order that the soft cathode beam could be easily adjusted through a hole in the diaphragm, *D*, fall upon the fluorescent screen, *S*, and there produce a spot of maximum brightness. This double adjustment is necessary, for it is impossible to assure by construction the exact direction of the beam.

If a very weak magnetic field is placed at right angles to this beam of slow moving electrons, the beam will be deflected and the bright spot shifted on the fluorescent screen. When the magnetic field is alternating or pulsating, the rapidly moving spot will cause a line to be seen on the screen. If this line is observed in a mirror rotating at right angles to it, the line is spread out into a curve representing the variations in the current of the coil which excites the magnetic field.

The coil used had about 3,000 turns of No. 26 enameled copper wire wound in two sections and mounted so that it could be fitted closely to the neck of the tube.

It might be advantageous to note briefly some of the details necessary in constructing and operating the hot-lime-cathode Braun tube.

- (1) The cathode should be adjustable in order to get a spot of maximum brightness.

- (2) A diaphragm, *D*, is necessary to eliminate extraneous light from the hot platinum strip and to stop down the divergent cathode beam.

- (3) The cathode should be as near the fluorescent screen as the sensitiveness of the apparatus permits.

- (4) CaO mixed with a small quantity of BaNO_3 insures a longer life to the lime and may be easily applied as a paste.

- (5) The anode should be near the cathode, for instance, 1 cm. distant.

- (6) The potential may be as low as 300 volts and preferably from a constant source, as from storage cells.

- (7) The pressure must be very low and may even be assisted with charcoal and liquid air. Gases are given off from

the lime cathode freely and necessitate constant pumping if the tube is to be used for any length of time.

With this hot-lime-cathode apparatus it was easy to observe in the rotating mirror the forms of the current curves when a spark passed and when the current flowed through the corona tube. The field coil was connected in series with the circuit: (1) between the spark gap and the corona tube, and (2) between the corona tube and ground or negative terminal of the generators (see Fig. 52). The current forms are sketched in Fig. 57 as they were observed in both of these positions and for the conditions (*N*) when there was no spark, (*S*) when sparks were passing slowly, and (*F*) when sparks were passing rapidly.

With the coil in the position (1) and with no spark, the current, N_1 , was observed to be a unidirectional one with an irregular and ragged edge. These irregularities are noticeable and are probably due to poor commutation at the machines as well as fluctuations in their speed of rotation.

With a few sparks passing, for instance, three per second, the current, S_1 , suddenly jumps to a maximum each time a spark passes and then more gradually falls to zero. The current is always in one direction and its maximum value is larger than N_1 .

When the spark gap is adjusted so that sparks pass more rapidly, the current, F_1 , has the same shape as S_1 except that the impulses are crowded closer together.

With the field coil connected in the position (2), without spark, the current, N_2 , is constant and gives a straight line.

With only a few sparks per second a peaked current form, S_2 , rises rapidly and decays more slowly than in S_1 .

For a greater frequency of sparks the ionization comes into play in a more pronounced fashion. The ionization current does not have time to reduce to zero between consecutive impulses from the spark, and so the resultant effect is a direct current, F_2 , ordinarily called a pulsating current, with peaks that correspond to the sparks passing on the other side of the tube.

These current forms are essentially the same both when the wire is positive and negative. They show directly that there are no oscillations in the series spark nor in the corona tube. If there were surges or oscillations left, they would have to be exceedingly weak and

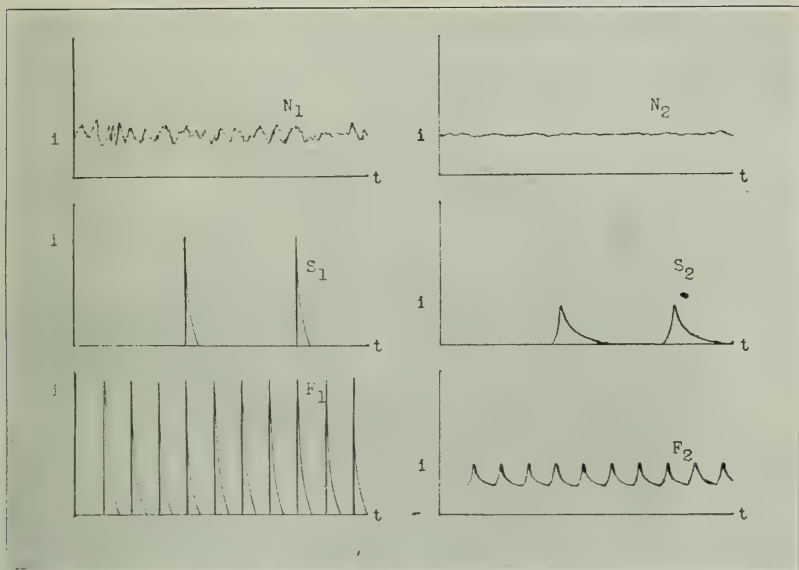


FIG. 57. CURRENT FORMS IN THE SPARK AND CORONA TUBE

of very high frequency. The results of these three methods show conclusively that the corona current with a spark in series is only intermittent and not oscillatory.

32. *The Corona and the Arc*.—Electrical discharges in gases at pressures near that of the atmosphere may be divided into five classes. These are:

(1) The dark discharge, where a small current passes through gas without making itself visible.

(2) The glow discharge, where a larger current passes and the gas in the immediate neighborhood of the electrodes becomes faintly luminous.

(3) The brush discharge, such as that from points where the glow is irregular and extends into the gas some distance from the electrodes.

(4) The spark discharge, which is a transient phenomenon bridging the whole distance between the electrodes, accompanied by a bright light and a comparatively large current.

(5) The arc, in which a large current passes between the electrodes in the gas and the ionized vapors of the electrodes producing a continuous light.

Any one of the first forms of discharge may be converted into any one of the latter forms by an increase in the potential between the electrodes, depending upon the nature and pressure of the gas, and the spacing, size, capacity, and shape of the electrodes.

The corona may be classed as a glow discharge like the positive wire without a spark, or as a brush discharge like the negative beads or the positive streamers. This glow or brush discharge easily goes over into the arc, and in the following paragraphs this transaction will be considered.

It has often been observed that an arc easily forms in the tube when the line switch connecting the tube is opened, especially when the wire in the corona tube is positive and a fairly large current is passing in the discharge. The conclusions drawn from the available data are as follows:

(1) For a given configuration of electrodes the arc-over takes place as soon as the current has reached a certain value which is nearly constant for all pressures.

(2) Arc-over occurs at lower voltages for smaller wires.

(3) At low pressures arc-over for the negative wire occurs at less voltage than for the positive wire.

(4) At high pressures (near atmospheric) arc-over for the positive wire takes place at a less voltage than for the negative wire.

The water resistance connected between the generators and the main bus bar was replaced by a 0.5 ampere fuse in order to see if it had any effect on the corona discharge with and without a spark. The visual forms were studied with the coaxial cylinders (the inner one being No. 20 copper wire) as well as with parallel (No. 20 copper) wires as electrodes.

With the cylindrical electrodes the general results obtained showed that the usual characteristic visual forms of the corona discharge were not materially altered for positive wire or for negative wire with and without a series spark. The only noticeable change was an increased brightness in the positive uniform glow, streamers, and negative beads. With the water resistance cut out the available energy was increased about one hundred times or, in other words, to 10 kilowatts. The negative beads and the positive streamers while much brighter were also in a more agitated state than before the increase in energy. They moved rapidly back and forth on the wire and would go over into the arcing stage much easier than they would with water resistance connected. The axial wire was No. 20 copper tightly stretched, but it was easily set into violent vibrations, at 739 mm. pressure and 12,700 volts, within a few seconds after closing the line switch. The applied potential fluctuated at times as much as 100 volts and the result was a more unsteady discharge. The water resistance has the effect of damping out the smaller variations.

The ease with which the arc formed was also noticed in experiments with No. 20 wires strung parallel with each other, placed $\frac{1}{8}$ inch apart and sealed into a glass tube.

With hydrogen it was noticed that when the wire was at a given potential above the critical glow voltage, the current in the beads would increase with the time, the beads would increase in size and

in a short time would combine to form an arc. Detailed observations were made on this point.

After the switch was closed, several beads were formed which soon combined into one much larger and brighter, as shown in Fig. 58. This bead seemed to take hold on the wire at a surface irregularity and remained fixed. A bright reddish spot on the wire formed the base of the bead, while a bright blue-white core extended from this spot toward the bright spots on the edge of the observation slot and shaded off into a milky glow or brush. As time proceeded the core grew larger and brighter and the milky glow of the brush reached farther toward the tube, as in *B*. Soon a faint reddish glow, *C*, appeared in the gas, proceeded from the bright spots on the tube, and extended toward the bead. This glow continued to increase in

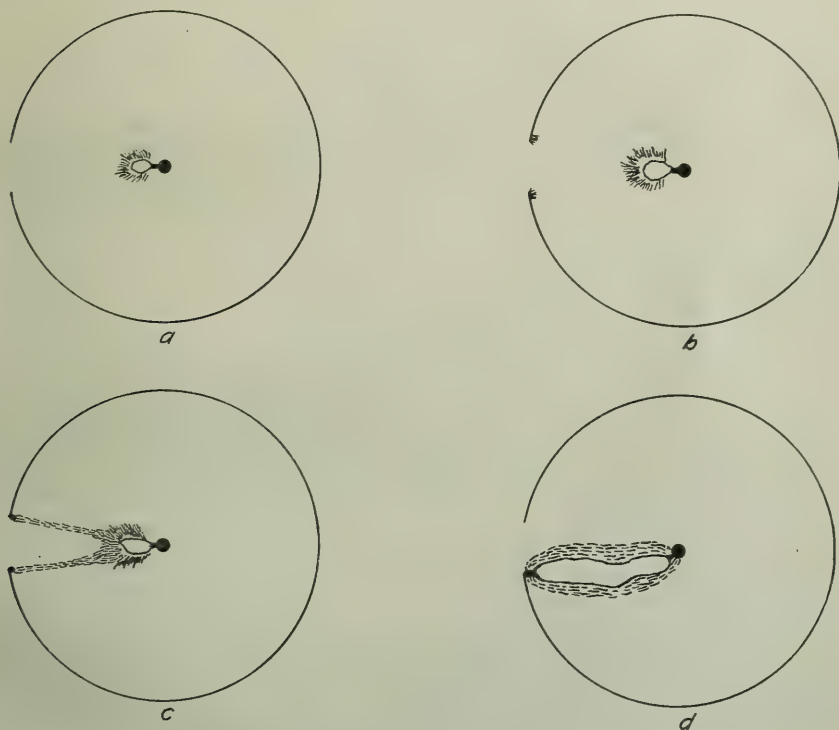


FIG. 58. EVOLUTION OF BEADS INTO THE ARC

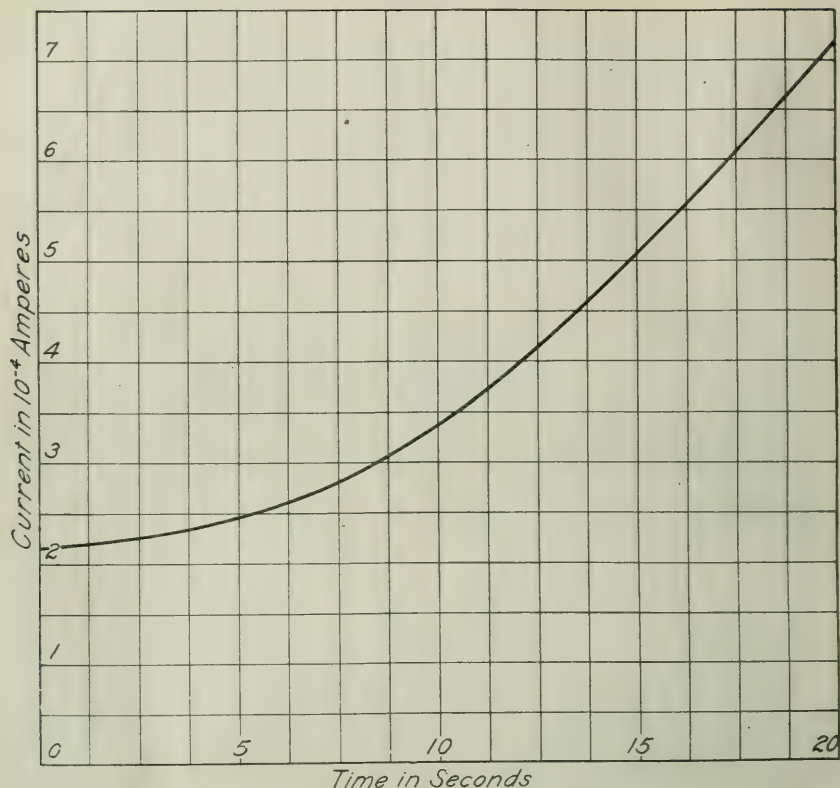


FIG. 59. CURRENT INCREASE WITH TIME FOR POSITIVE STREAMERS

brightness for a short time until the arc, *D*, flashed into existence. The arc had a very bright tubular blue-white core surrounded by a hazy reddish glow and extended from a bright reddish spot on the wire to bright white on the tube. The negative beads and perhaps the positive streamers may be spoken of as miniature or beginning arcs which unite to form a single arc when the current density reaches a certain value.

The curve in Fig. 59 will serve to show how the current in the streamers increases with the time. At a potential of 11,850 volts, somewhat above that for starting corona glow in air at 751 mm. pressure, a spark gap of 0.18 mm. length was placed in series with the tube. Readings of the current were taken at intervals of 5 sec-

onds and when plotted resulted in the given curve. An arc passed shortly after 20 seconds, but the maximum current before it occurred was not obtained.

The increase of the current depends largely on the sparking distance and on the applied voltage (see curve *a*, Fig. 60). When the spark distance from zero is increased, the current for the positive corona decreases accompanied by a decreased brightness of the uniform glow, reaches a minimum value, and as the streamers appear rises to a maximum rapidly and falls off to zero for a large spark distance. The streamers are brightest at the maximum current value and are always connected with a large current. The corresponding negative curves show no such a maximum, with increasing voltage the positive current increases very rapidly.

In order to test the relative magnitude of the current due to the accumulation of ions and that due to the spark, a current-spark dis-

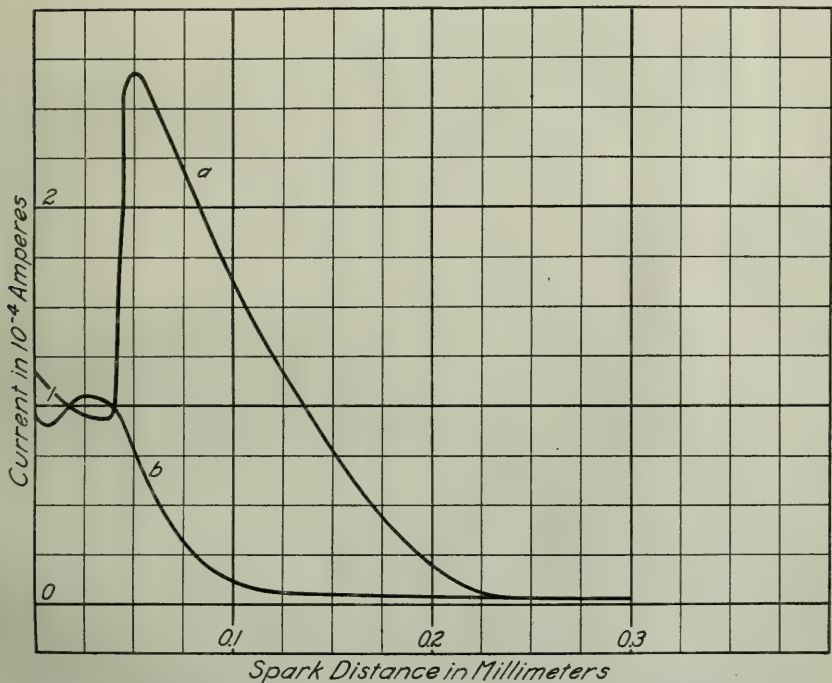


FIG. 60. CURRENT CHANGE FOR VARYING SPARK DISTANCE

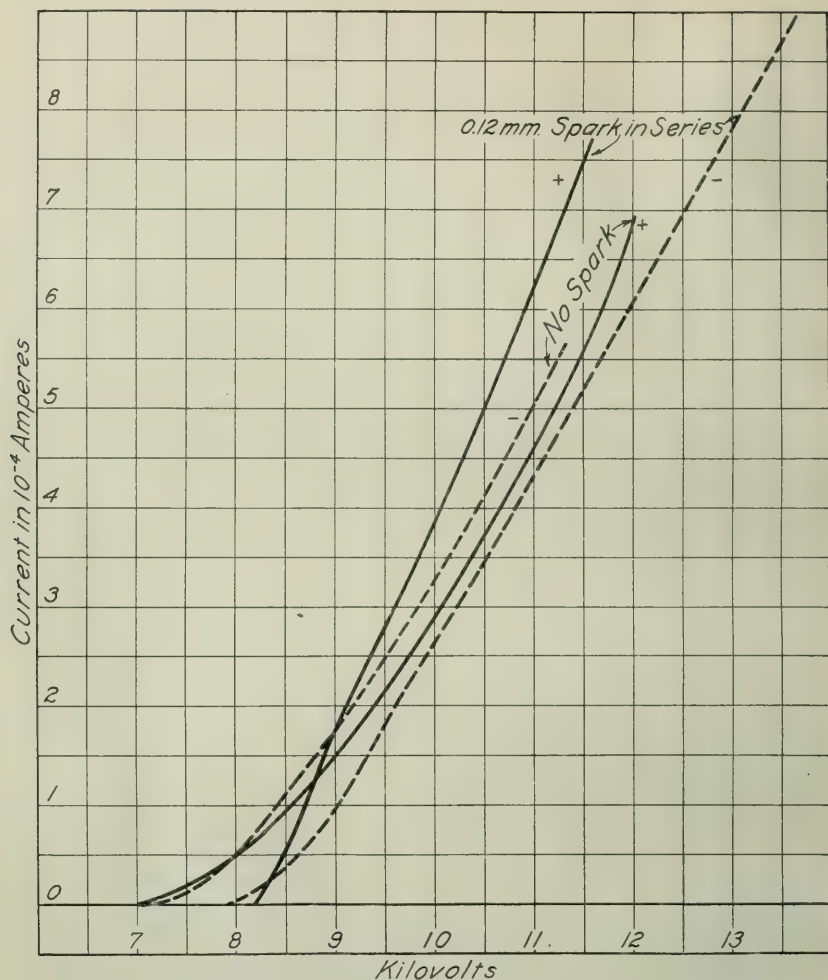


FIG. 61. CHARACTERISTIC CURVES WITH AND WITHOUT SERIES SPARK

tance curve was taken, when the tube was closed, and another when a small current of air was passing through the tube sweeping out some of the ionized gas.

The curves are given in Fig. 60, curve *a*, being taken with the tube closed using a potential of 11,850 volts, and curve *b* with a stream of air passing which necessitated a higher corona voltage; namely, 13,100 volts.

Curve *b* still has the characteristic maximum in the curve, but it is very much reduced in size, whereas curve *a* has a very pronounced maximum of a large value. These curves portray in a striking manner the effect a short spark has in producing a very great ionization in the gas, and also makes it easy to conceive how the positive arc takes place so readily when the switch remains closed for a little time or is suddenly opened while a large current is passing in the tube.

The ordinary characteristic current-voltage curves as obtained in the process of experiments without a series spark give the negative characteristic as lying above the positive. This relative position is maintained in all cases, with one or two minor exceptions.

When a short spark is placed in series with the corona, these positions are reversed and the positive curve lies above the negative, except at the starting point where the curves cross and give a lower starting potential for the negative wire (See Fig. 61). The starting potential with the spark in series is, however, higher than for the other case. It might be pointed out also that the characteristics taken with a series spark are more widely separated than those taken without, and thus they show a wider variation in the current from the positive and negative wires for a given voltage.

It was found when the spark gap was closed while current was flowing that the current would drop in a short time to a position on the ordinary characteristic curve. If the wire is positive at 11,000 volts and a 0.12 mm. spark is in series, for instance, a current of $6.2 \cdot 10^{-4}$ amperes will flow. Short-circuiting the spark gap will cause the current to drop to the value $4.6 \cdot 10^{-4}$ amperes which is a point on the ordinary positive characteristic curve. Similarly by short-circuiting the spark gap when the wire is negative the current will increase to a value which lies on the ordinary negative characteristic. These observations again show that the positive streamers carry a large current.

Without a spark gap in series with the tube, the ordinary uniform positive glow is formed by ionization in the gas near the wire where the field strength is greater than thirty kilovolts per centimeter, the current being carried by both positive and negative ions. The usual negative corona discharge begins critically as a uniform glow similar to that of the positive discharge but has a greater thickness. The brushes or negative beads, soon formed by a slight potential

increase, bear a similarity to the arc. This fact, in addition to the position of the negative characteristic curves and to the influence which the surface condition and the material of the wires have on the beads, leads to the belief that an electron emission is present in addition to ionization by collision in the gas.

The case is somewhat different when a series spark gap is used. The corona tube may be considered as a leaky condenser connected in series with a spark gap and a constant source of high potential. A charge will build up to the condenser until the potential difference of the spark gap is sufficient to break down the air between the electrodes. An instantaneous unidirectional current will glow across the spark gap and at the same time the potential across the tube will increase to a point where the corona is formed. The current now passing through the tube will immediately reduce the potential of the spark gap below its critical point and the circuit will be broken. The process is then repeated.

The more nearly uniform appearance of the negative corona can now be explained as a super-imposed building-up and decay of the negative glow discharge through its different stages as the potential on the tube fluctuates. The positive streamers have at times been observed at critical voltages on rough wires when no spark was in series. These streamers are similar to the positive brush discharges observed from pointed electrodes maintained at high positive potentials. Their characteristic presence in the corona tube when a spark is in series is due probably to the sudden impression of a strong field and may be accompanied by a discharge of positive metallic ions, since it has been observed that the surface of the wire becomes disintegrated at points where these streamers are maintained.

The following conclusions have been made:

- (1) A spark gap in series with the discharge tube affects the positive and negative corona in very characteristic and striking ways.
- (2) The changes are due to intermittent currents.
- (3) A hot-lime-cathode Braun tube has been developed and used in observing the weak pulsating currents which pass through the spark and the corona tube.
- (4) Evidence has been given to show the relation of the corona to the arc discharge.
- (5) An attempt at an explanation of the pulsating current has been made.

CHAPTER XI

OTHER TYPES OF CORONA DISCHARGE

Two wires, 0.167 mm. in diameter, were arranged parallel, two centimeters apart, inside a glass tube. Photographs given in Fig. 62 were taken showing the discharge between parallel wires at reduced pressures with and without a series spark. The three lower half-tones show the typical isolated brush discharge on the negative wire with corresponding luminous sections of the positive wire. The negative brushes had a brilliant nucleus with a fainter glow spreading out from it. For pressures lower than those for which the photographs were taken, the discharge became more brilliant; the brushes spread further apart and increased in size. Each section of the positive glow was usually of uniform brilliancy. For comparatively low pressures and high voltage the positive sections became somewhat discontinuous, and bright spots mixed with the uniform glow.

Two No. 36 wires were stretched three centimeters apart over hard rubber bridges in order to be parallel and the discharge between them was studied. When the visible discharge was fairly started, it took the form of a uniform continuous glow along the negative wire. It was discovered that the humidity of the air had a marked effect upon the discharge.

The introduction of a short spark in series made a marked change in the nature of the discharge. Both wires were more or less completely covered with a nearly uniform glow and there was no longer any marked difference between positive and negative (see Fig. 62). At low pressures and relatively high voltage the discharge between the wires resembled a sheet of luminous rain. An intermediate effect had bluish streamers between the wires.

A platinum tip was arranged to be moved from one wire to the other and thus, as shown in Chapter VII, the distribution of potential between the wires was determined. Three explorations were made,—namely, when the voltages were 8,000, 10,000, and 12,000 volts.

Fig. 63 shows the curves for the field distribution and also the distribution of the field as calculated from the electrostatic formula.

The curves show that the actual distribution of the field departs widely from the electrostatic formula, especially at the lower voltages. A large anode and cathode fall of potential exists.

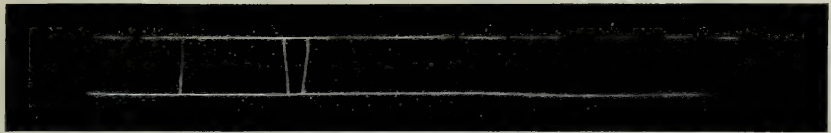
A study of the corona on a wire at the axis of a short cylinder was undertaken in order to increase the knowledge concerning the losses which occur in high voltage transformer bushings, in wall, ceiling and line insulators. For preliminary experiments it was decided to have air as the insulating medium and to use a wire passing through the axis of a short cylinder.

The apparatus consisted of an aluminum disc, 2 mm. thick, with a round hole 16 mm. in radius at its center, placed in a horizontal plane. A vertical wire passed through the center of the hole. This apparatus was enclosed in a glass jar so that dry air could be admitted.

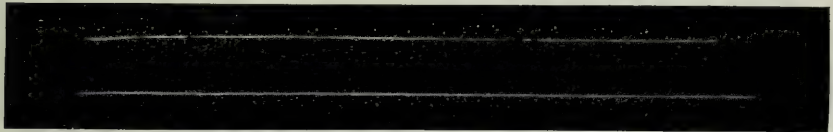
The visual phenomena of this corona depend on the polarity as in the case of coaxial cylinders, but the variety of the phenomena is even greater. If the wire is positive, the corona is uniform along the wire over a large range of voltages and pressures. Below 130 mm. of mercury pressure the typical positive glow will collapse to a much shorter and brighter glow, a few seconds after the switch is closed. After the voltage is increased, the luminous strip on the positive wire takes its final form of a triangular flag diverted toward the negative bead on the disc. With increasing voltage, the negative head on the disc becomes brighter and is accompanied by a ring of light along the edge of the disc. The colors of the positive and negative glow are distinctly different.

If the polarity is reversed, the wire becomes negative, the disc becomes positive and the positive glow, at first uniform along the edge of the disc, breaks into distinct beads. These positive beads move around the periphery of the disc, while at the same time the negative bead travels up and down along the vertical wire. This phenomenon is illustrated by Fig. 64. For higher pressures there appears a large number of negative beads on the central wire accompanied by a weak, uniform, circular, positive glow along the edge of the disc. A spark in series with this corona modifies the appearance in a way analogous to that of the coaxial cylinders.

The starting point of the corona for positive and negative wires has been observed; the results resemble those obtained in the fore-



(a) ARC IN SERIES, PRESSURE 312.2 MM., VOLTS 8000, AMPERES 1.80×10^{-4}



(b) ARC IN SERIES, PRESSURE 312.2 MM., VOLTS 8000, AMPERES 1.14×10^{-4}



(c) NO ARC, PRESSURE 312.2 MM., VOLTS 8000, AMPERES 2.35×10^{-4}



(d) NO ARC, PRESSURE 450.0 MM., VOLTS 8700



(e) NO ARC, PRESSURE 450.0 MM., VOLTS 8400

FIG. 62. CORONA BETWEEN PARALLEL WIRES AT REDUCED PRESSURES
LOWER WIRE IS POSITIVE IN EVERY CASE

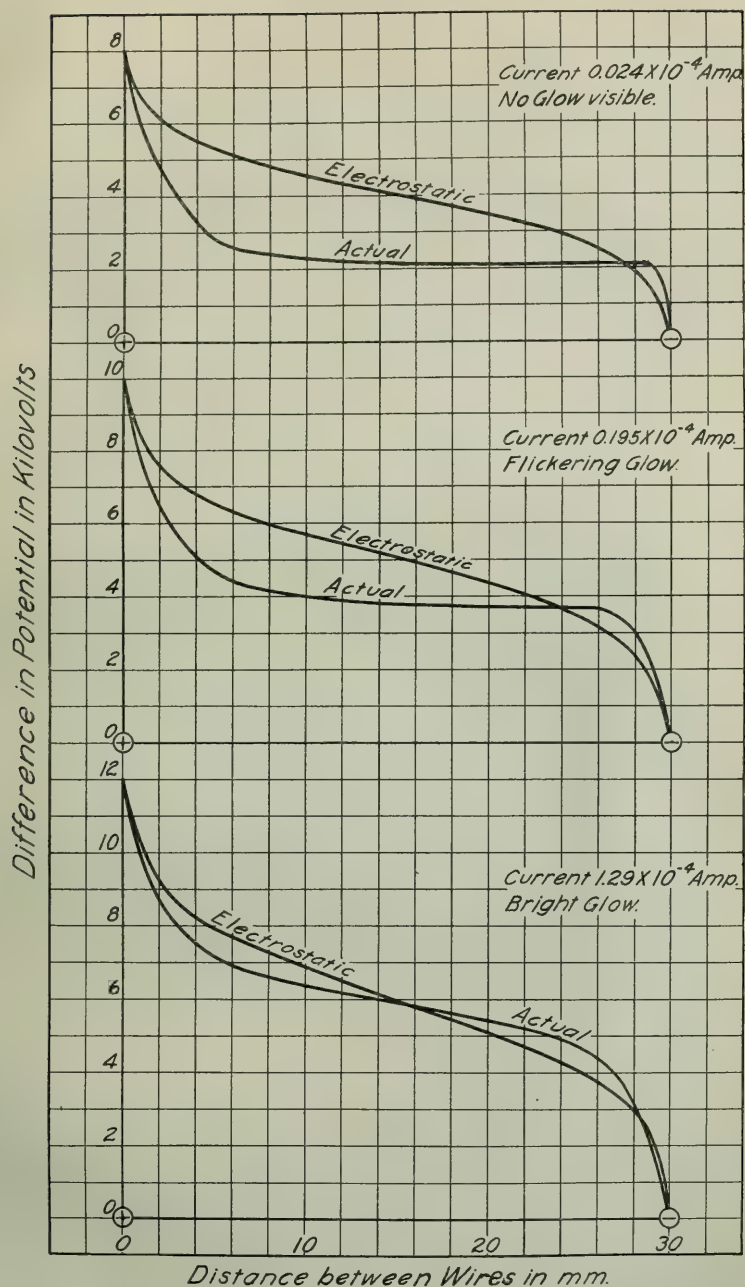


FIG. 63. FIELD DISTRIBUTION BETWEEN TWO PARALLEL 36 B. AND S. GAGE WIRES
3.0 MM. APART

going. The characteristic curves also are similar to those obtained with wire and cylinder.

The experimental knowledge of the corona is still very incomplete. Little has so far been done in the spectroscopic analysis of the various light phenomena which accompany the corona. It has been found, for instance, that the negative beads in hydrogen do not give the characteristic series lines of hydrogen, but rather a continuous band in the red and yellow region of the spectrum. It is hoped the knowledge in this field will be increased in a short time. Mechanical vibrations of the wires and an electric wind have been mentioned occasionally, but these phenomena also require further study.

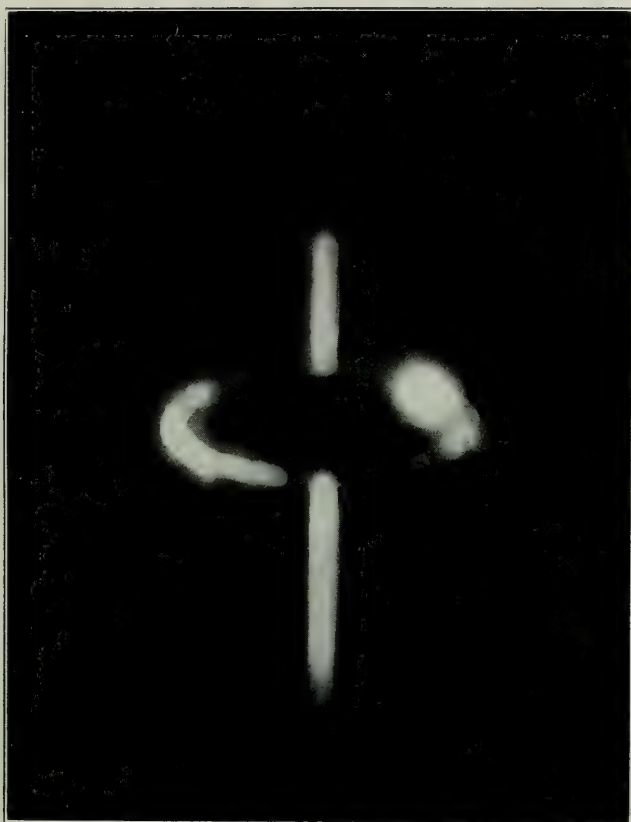


FIG. 64. CORONA ON A WIRE AT THE AXIS OF A SHORT CYLINDER

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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN No. 115

NOVEMBER, 1919

THE RELATION BETWEEN
THE ELASTIC STRENGTHS OF STEEL
IN TENSION, COMPRESSION, AND SHEAR

BY

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THE RELATION BETWEEN THE ELASTIC STRENGTHS OF STEEL IN TENSION, COMPRESSION, AND SHEAR

I. INTRODUCTION

1. *Preliminary.*—This bulletin presents the results of experiments with six grades of steel, three carbon steels and three alloy steels; namely, soft, mild, and medium carbon steel; and vanadium, nickel, and chrome-nickel alloy steel. The elastic strength in tension, in compression, and in shear is given for each of the six grades of steel. The elastic strength in shear is found from tests in torsion with solid cylindrical specimens and with thin-walled hollow cylindrical specimens. Furthermore, a factor is found by the use of which the true or correct shearing elastic strength may be calculated from the elastic strength obtained from a test of a solid specimen. The ratio of this true elastic shearing strength to the elastic tensile strength is given for each grade of steel and its bearing on the theory of combined stress is discussed. The ratio of the elastic tensile strength to the elastic compressive strength is also given and the effect of the amount of rolling upon the elastic tensile and compressive strengths is discussed. The effect of the direction of rolling upon all three elastic strengths is considered for one of the materials; namely, nickel steel.

Our knowledge of the breakdown of elastic action of ductile materials, particularly in the case of combined loading, is far from complete. The various theories of combined stress lead to results which differ rather widely when applied to various machine parts or to structural elements, such as thick cylinders, flat plates, crank shafts, webs of girders, etc. The maximum shear theory of combined stress for ductile materials as expressed by Guest's law, which has gained rather wide acceptance in recent years, assumes that the elastic shearing strength is one-half of the elastic tensile strength. Available experimental results, however, have, in general, failed to justify this assumption. The importance of the limitation imposed by the shearing stress upon the elastic strength of ductile material is, of course, generally recognized. If the maximum strain theory holds until the shearing yield point is reached, as is indicated in recent tests,* it is of

*See Bulletin No. 85, Engineering Experiment Station, University of Illinois, "Strength and Stiffness of Steel under Biaxial Loading," by A. J. Becker.

special importance to know the relation between the shearing and the tensile (and compressive) elastic strengths for various grades of ductile and semi-ductile steels. The main object of the investigation herein recorded was to determine carefully the elastic shearing strength of ductile and semi-ductile steel and to find the ratio of the elastic shearing strength to the elastic tensile strength with the hope that definite information would thereby be obtained on the breakdown of the elastic action of various grades of steel and on the limits of the theories of combined stress.

Apart from the problem of combined stress there has been also a lack of knowledge of the correct elastic shearing strength of various grades of steel and of the general nature of elastic shearing failure as well as of methods of determining the correct shearing strength from tests.

The facts brought out in connection with the elastic compressive strengths of the various materials tested should also add to our knowledge of the elastic behavior of steel and it is felt that questions are raised which may become of considerable importance. There is some evidence indicating that the amount of rolling (roughly indicated by the thickness of the rolled material) may become an important factor in the selection of the proper criterion of elastic strength as well as in estimating the elastic compressive and shearing strengths from a tension test. This question may be of considerable importance in connection with compression members and with certain cases of combined stress. It may also have an important bearing on the problem of the fatigue of steel under repeated stress.

The severe uses under the many and varied new conditions, such as have arisen during the war, and the development of new requirements for machine parts have brought out the need for fuller information on the physical properties of carbon and alloy steel. This bulletin is presented as a contribution toward filling this need.

2. *Acknowledgment.*—All of the experimenting was done in the Laboratory of Applied Mechanics of the University of Illinois. Acknowledgment is made to Professors A. N. TALBOT and H. F. MOORE for the interest shown and helpful suggestions offered during the investigation. Some preliminary experimenting had been done by Professor MOORE to determine the merits of various forms of shear specimens. This work was found to be of considerable value in planning certain parts of the investigation herein described.

II. MATERIALS, TEST SPECIMENS, AND METHOD OF TESTING

3. *Materials*.—As already stated, six grades of steel were tested; namely, soft, mild, and medium carbon steel, and vanadium, nickel, and chrome-nickel alloy steel. Chemical analyses were made of the nickel steel and the chrome-nickel steel only. All of the material except the nickel and the chrome-nickel steel was bought in the open market. The nickel steel specimens were cut from one of the ends of the untested riveted-joint test specimens made for the Board of Engineers of the Quebec Bridge. (The other riveted-joint specimens were tested at the University of Illinois and a report of the tests was made in Bulletin No. 49 of the Engineering Experiment Station.) The chrome-nickel steel specimens were made from $\frac{3}{4}$ -inch square bars of the same material as that used in the chrome-nickel steel riveted-joint specimens also described in Bulletin No. 49 referred to above. The chemical analyses of these two alloy steels as reported in Bulletin No. 49 are given in Table I.

TABLE 1
CHEMICAL COMPOSITION OF NICKEL AND CHROME-NICKEL STEEL

Element	Nickel Steel Per Cent	Chrome-Nickel Steel Per Cent
Carbon.....	0.258	0.191
Sulphur.....	0.008	0.035
Phosphorus.....	0.044	0.042
Manganese.....	0.700	0.485
Nickel.....	3.330	0.733
Chromium.....	.....	0.170

All of the specimens of chrome-nickel steel did not come from the same bar. Three different bars rolled from the same heat were used. The medium steel specimens were made from two bars supposed to be of the same material and billed as 40-point carbon steel. The specimens of each of the other four materials were made from the same bar or piece. All of the material was hot-rolled only. No cold-rolled material was used. The specimens of soft steel came from a bar $3\frac{1}{2}$ inches in diameter by 20 feet in length. The mild steel specimens and

also the vanadium steel specimens were cut from a bar $\frac{7}{8}$ inch in diameter by 16 feet in length; the nickel steel specimens were cut from a slab 2 inches in thickness by $7\frac{1}{2}$ inches in width. The large soft steel bar ($3\frac{1}{2}$ inches in diameter) was used in order to obtain large torsion specimens as well as small ones.

Although the chemical analysis of all of the materials tested can not be given, the range of material used is well indicated by the elastic tensile strengths as given in Table 2. While some of the material used did not have a well defined yield point, yet all six grades of steel are considered to be ductile or semi-ductile material since the tensile fractured area in all cases showed a considerable reduction.

TABLE 2
ELASTIC TENSILE STRENGTHS OF MATERIALS USED

	Materials	Elastic Strength* lb. per sq. in.
Carbon Steel	Soft	21 000
	Mild	32 800
	Medium	45 000
Alloy Steel	Vanadium	52 500
	Nickel	38 000
	Chrome-nickel	35 300

*Proportional limit (see Fig. 5) is here used as a measure of the elastic strength.

4. *Test Specimens.*—Tension, compression, and shear (torsion) specimens were made from each of the six materials. Both solid and hollow cylinders were used for the torsion specimens; hollow specimens of three different wall thicknesses were tested. In general from three to nine specimens of each type were tested for each material. The total number of specimens tested was 160, exclusive of a considerable number used in preliminary tests in perfecting the measuring apparatus. In obtaining specimens from a bar, care was taken to cut the specimens in rotation so as to avoid the effects of any systematic variation in the properties of the material along the bar. In the case of nickel steel, specimens were cut from a slab 2 inches thick by $7\frac{1}{2}$ inches wide in such a way that the longitudinal axes of some of the specimens were parallel to the direction in which the slab was rolled, while the longitudinal axes of other specimens were perpendicular to the direction of rolling. Large torsion specimens both solid and hollow, as well as small ones, were made from the $3\frac{1}{2}$ -inch bar of soft steel.

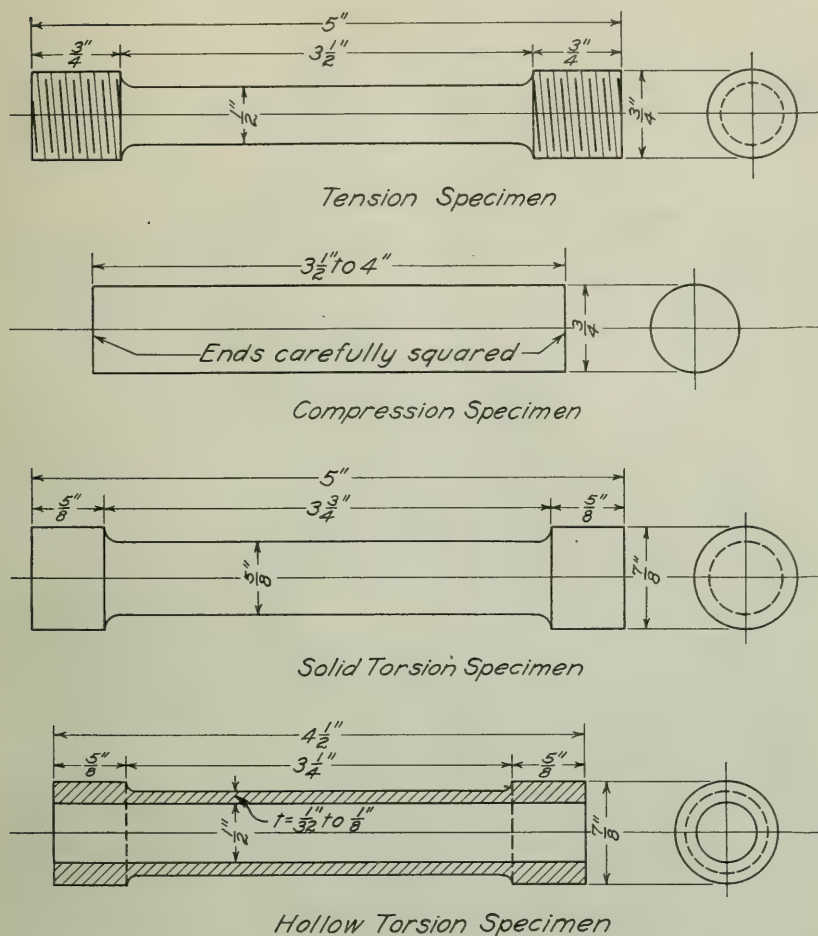


FIG. 1. FORM AND DIMENSIONS OF SMALL TEST SPECIMENS

Fig. 1 gives the dimensions of the small specimens used for all the materials and Fig. 2 gives the dimensions of the large specimens of soft steel. Fig 3 shows some of the specimens both before and after testing and also the apparatus used for measuring the thickness of the walls of the small hollow specimens. The length of the small hollow specimens was limited by the length of the $\frac{1}{2}$ -inch hole which could be drilled through the specimens from one end. The large hollow specimens were first drilled from both ends and then bored out to the

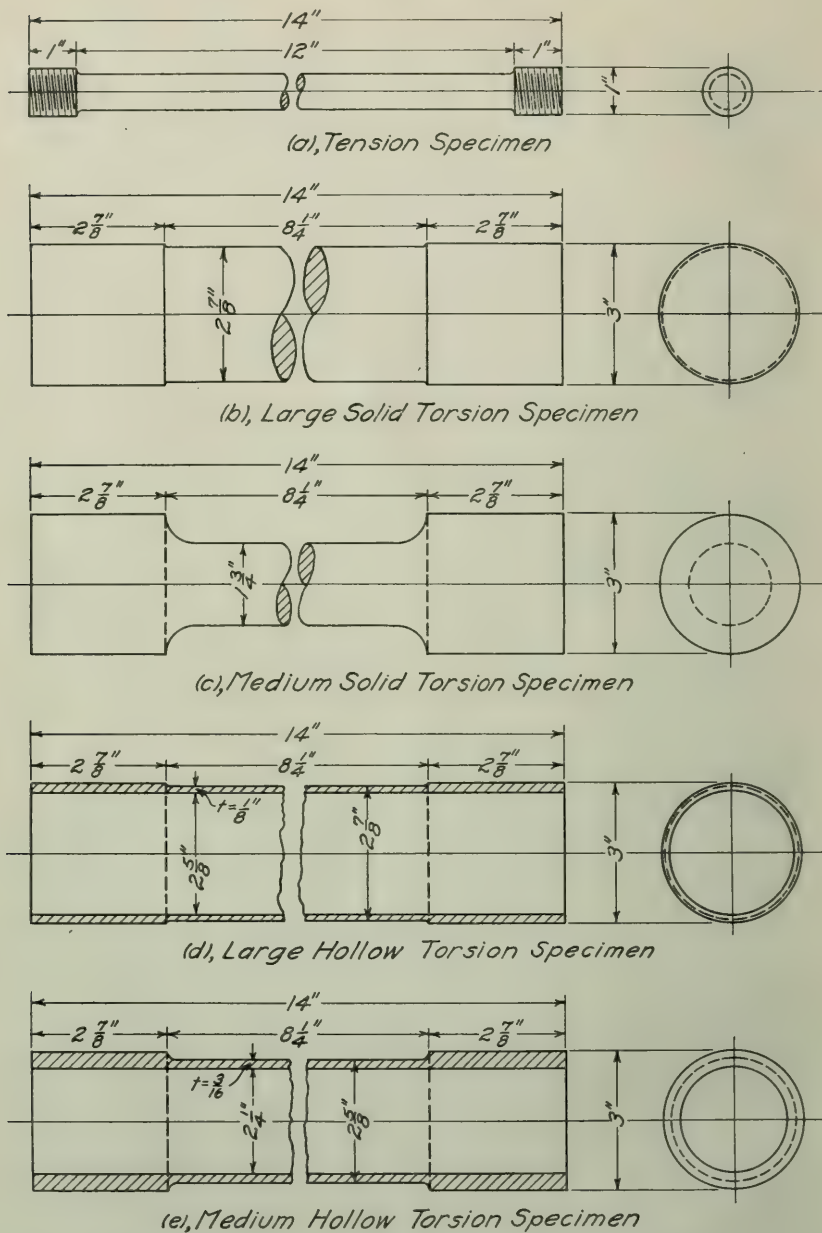


FIG. 2. FORM AND DIMENSIONS OF LARGE TEST SPECIMENS

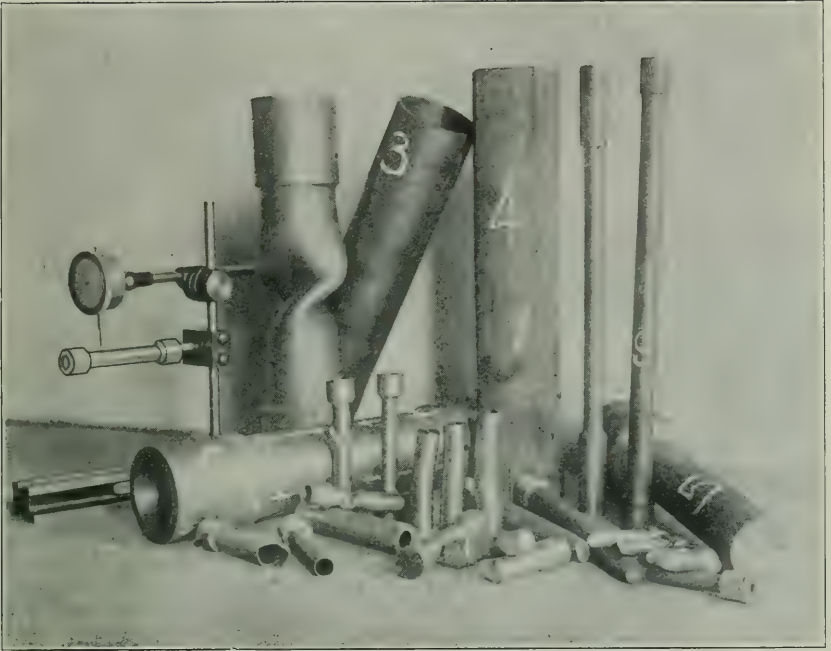


FIG. 3. VIEW OF SOME OF THE SPECIMENS

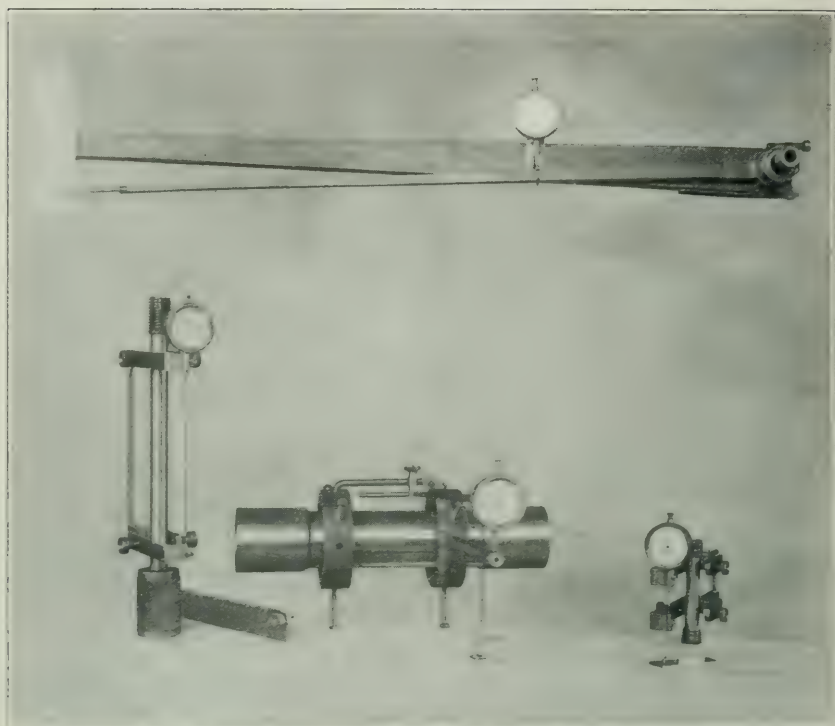


FIG. 4. VIEW OF DEFORMATION MEASURING APPARATUS

desired inner diameter. After the desired inner diameter was obtained, each specimen, whether small or large, was mounted on a mandrel and the outside diameter turned down to the required dimension. The wall thickness of the hollow specimens was measured at four points, 90° apart, around each of four sections along the length of the specimens. The outside diameters at each of the four sections were also taken and the smallest cross section was used in the calculations. The wall thickness could be read to 0.0001 inch. In the case of the large hollow specimens the wall thickness was found in the same way although larger apparatus was required.

5. *Tension Tests.*—The tension test specimens were made with threaded ends and with a diameter of $\frac{1}{2}$ inch (see Figs. 1 and 2). A 2-inch gage length was used with all the specimens except those of soft steel with which a gage length of 8 inches was used. The long specimens of soft steel were used in order to determine the modulus of elasticity more accurately than could be done with specimens having a 2-inch gage length. The modulus of elasticity or stiffness of the various materials, however, is not discussed in this bulletin.

All of the tension tests were made in a 100 000-pound Riehle universal testing machine which had been calibrated over the range used in these experiments. Spherical seated holders were used in all of the experiments.

The extensometers used are shown in Fig. 4. The unit-elongation could be read directly to 0.00025 inch per inch when using a 1/1000-inch Ames dial for a 2-inch gage length, or to 0.000025 inch per inch when using a 1/10 000-inch Ames dial. Both dials were used but it was found that there was little advantage in using the more sensitive dial. The unit-elongation could be estimated to one-tenth of the above values.

6. *Compression Tests.*—The compression test specimens in nearly all cases were made with a diameter of $\frac{3}{4}$ inch and with a length of $3\frac{1}{2}$ inches to 4 inches as shown in Figs. 1 and 3. A gage length of 2 inches was used in all cases and the deformation measuring apparatus was the same as that used in the tension tests. Care was taken to square off the ends of the specimens in the lathe so that they were smooth and perpendicular to the axis of the specimens. Each specimen was carefully centered in a 100000-lb. Riehle universal testing machine by means of a templet; spherical seated bearing blocks were

used. The testing machine had been calibrated over the range used in these experiments and for a considerable number of tests it was the same machine as was used for the tension tests. The length of specimen used ($3\frac{1}{2}$ inches to 4 inches) corresponds to a slenderness ratio value of 19 to 21. In most cases the specimen failed as a flat-ended column (see Fig. 3). It is felt that with the very careful centering the real elastic strength of the material was developed in all cases although the ultimate compressive strength showed considerable variation.

7. *Torsion Tests.*—After some preliminary study and experimenting, a torsion test of a cylindrical specimen was decided upon as being the most satisfactory means for determining the elastic shearing strength of the material. Both solid and hollow cylindrical specimens were used. The small hollow specimen (see Figs. 1 and 3) were made with three different dimensions of the wall thickness for several of the materials; namely, $\frac{1}{32}$ inch, $\frac{1}{16}$ inch, and $\frac{1}{8}$ inch (approximate dimensions), the nominal inside diameter being $\frac{1}{2}$ inch for each specimen. A wall thickness of $\frac{1}{32}$ inch makes it possible to determine, very closely, the true elastic shearing strength of the material.

In the case of soft steel, large solid and hollow specimens were made from the $3\frac{1}{2}$ -inch bar in addition to the small specimens already described. These large specimens were 14 inches long with a gage length of 5 inches and with a length of 8 inches between shoulders. The diameter, between shoulders, of the first large specimens made was $2\frac{7}{8}$ inches for both the solid and the hollow specimens. From the results of the tests, however, it was at first thought that the specimens were not long enough; hence one solid specimen was made 20 inches long and tested, but the results showed no effect due to the changed length. Three solid specimens were then made, $1\frac{3}{4}$ inches in diameter, for which the load on the machine at the yield point would be about the same as for the hollow specimens. The effect of this change is discussed later. The large hollow specimens were made in two sizes; namely, with a wall thickness of $\frac{1}{8}$ inch and an outside diameter of $2\frac{7}{8}$ inches and with a wall thickness of $\frac{3}{16}$ inch and an outside diameter of $2\frac{3}{8}$ inches, as shown in Figs. 2 and 3. In testing the former, plugs had to be fitted into the ends to keep the ends from collapsing in the grips, while in testing the latter this method was not necessary. The ratio of the wall thickness of the hollow specimens to the diameter for the thinner walled specimens is about the same for the large speci-

mens as for the small ones, the value of the ratio being approximately 1 to 20.

All of the large specimens were tested in a 230 000-inch-pound Olsen torsion testing machine, while the small specimens were tested in a Riehle hand power pendulum torsion testing machine. A special light pendulum was used in the Riehle machine for the hollow thin-walled specimens and special apparatus was made for measuring the load. Both torsion machines were calibrated carefully.

All of the small specimens from the $3\frac{1}{2}$ -inch bar of soft steel were made by first cutting a 14-inch length of the bar longitudinally into quarters and turning the small specimens from one or more of the quarters.

The apparatus for measuring the deformation in the torsion tests is shown in Fig. 4. Both a $1/1000$ -inch and a $1/10$ 000-inch dial were used on each apparatus, so that a considerable range in sensitiveness was obtained to suit the variations in wall thickness, etc.

III. EXPERIMENTAL DATA AND DISCUSSION

8. *Criteria of Elastic Strength.*—Perhaps the best indication of the elastic strength of a material is the elastic limit; that is, the greatest unit-stress which the material can resist without taking a permanent set. The process of determining the elastic limit, however, is so long that it was considered impracticable for the purposes of this investigation.

For the purpose of the comparison of the elastic strengths of various materials or of the same material under different types of stress any one of several unit-stresses as represented on the stress-strain curve may be used. Three such points on the stress-strain curve are used in this investigation; namely, the proportional limit (sometimes called proportional elastic limit), the yield point, and a point between the proportional limit and the yield point called the semi-elastic point or the useful limit point. It is assumed that elastic action only takes place until the proportional limit is reached, while plastic action only occurs at the yield point. Any point on the stress-strain curve between the proportional limit and the yield point corresponds to an action in the material which is partly elastic and partly plastic. Several arbitrary methods have been proposed for conveniently locating such a point. The semi-elastic point or useful limit point used in this investigation is defined as the unit-stress at which the rate of deformation is 100 per cent greater than at zero-stress. This point was used by the Committee of the American Society of Civil Engineers in the analysis* of the tests of large built-up-columns and is very similar to Johnson's apparent elastic limit.† In Fig. 5 the point *U* represents the useful limit point which is found by first laying off *KN* equal to two times *KM* and then drawing a line parallel to *ON* tangent to the stress-strain curve, the point of tangency being *U*. Fig. 5 also shows the proportional limit and yield point.

In the study of the elastic failure of the materials tested, the three criteria of elastic strength mentioned above (proportional limit, useful limit point, and yield point) taken together furnish a safer guide than any one alone. The elastic strengths of the materials tested as

*Proc. A. S. C. E. Dec., 1917.

†Johnson: *The Materials of Construction*, p. 10, 1918.

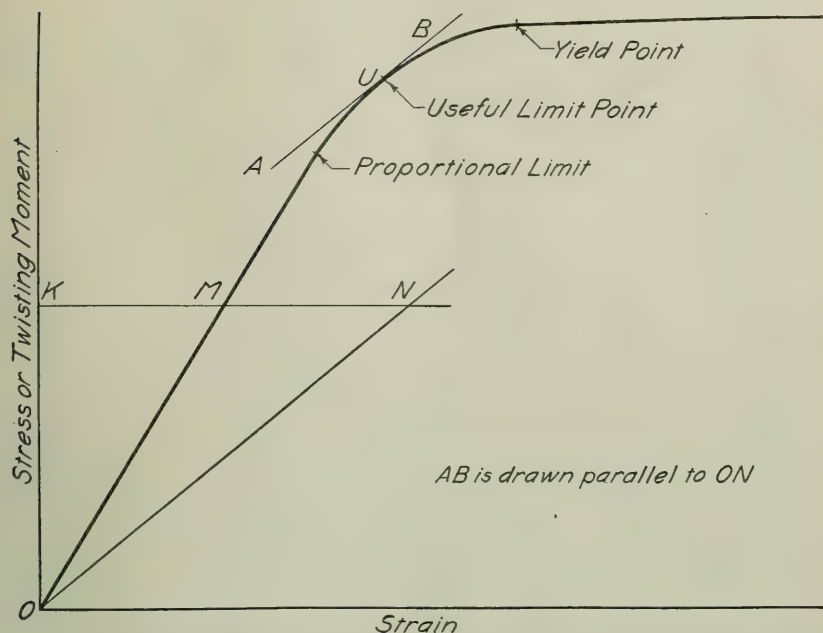


FIG. 5. TYPICAL STRESS-STRAIN DIAGRAM SHOWING THE USEFUL LIMIT POINT

indicated by each of these three criteria for tension, for compression, and for shear are given in Tables 3, 4, and 5 for the individual specimens while the averages are given in Table 6.

9. *Shearing Strengths.*—As has already been stated, the elastic strength in shear was found from tests of solid cylindrical torsion specimens and from thin-walled hollow cylindrical specimens.

It has been commonly recognized that the yield point in shear as found from the test of a solid cylindrical torsion specimen does not represent the correct shearing yield point of the material since all of

TABLE 3
RESULTS OF TENSION TESTS

Gage length 2 in. Diameter $\frac{1}{2}$ in. except as noted. Stress in lb. per sq. in.

Material	Mark	Proportional Limit S_p	Useful Limit Point S_e	Yield Point S_y	Ultimate Strength S_u	Elongation Per Cent	Reduction of Area Per Cent
Soft steel (diameter $\frac{3}{4}$ in.)	M3-1d	21 000	24 000	29 000	56 100	30.0*	50.6
	M3-T	22 500	27 000	29 000	53 100	50.0	57.6
	M3-2d	20 500	24 000	28 000	56 000	27.0*	53.5
	M3-3d	20 000	25 000	27 500	56 200	29.8*	55.5
	Average	21 000	25 000	28 400	55 400	28.9*	54.3
Mild steel	3	33 000	33 000	33 000	54 900	45.3	68.8
	11	33 000	33 000	35 500	55 500	42.0	70.0
	15	32 000	32 000	32 500	55 000	44.0	69.0
	7	33 000	33 000	33 500	54 300	43.5	63.8
	Average	32 800	32 800	33 600	54 900	43.7	67.9
Medium steel	4-3	46 000	46 000	46 500	77 900	33.5	57.6
	4-7	44 000	44 000	45 000	78 100	33.5	57.6
	Average	45 000	45 000	45 800	78 000	33.5	57.6
Vanadium steel	V-1	53 500	56 000	60 500	109 500	25.0	50.8
	V-3	53 000	54 500	59 000	108 000	23.5	50.8
	V-7	50 000	56 000	59 000	108 000	23.5	52.0
	V-15	53 500	57 000	63 000	110 000	15.6†	34.5†
	Average	52 500	55 900	60 400	109 000	24.0	51.2
Nickel steel Stress parallel to direction of rolling	P-1	35 500	39 000	47 000	87 800	28.5	57.5
	P-2	38 500	40 000	47 000	88 000	28.0	55.2
	Average	37 000	39 500	47 000	87 900	28.3	56.4
Nickel steel Stress perpendicular to direction of rolling	C-1	39 000	40 500	47 000	86 500	17.5	36.0
	C-2	41 000	41 500	48 000	88 100	24.0	51.2
	C2-1d	36 500	40 000	48 000	88 500	22.5	30.0†
	Average	38 800	40 700	47 700	87 700	21.3	39.0
Chrome-nickel steel	L-3	33 500	35 000	38 000	64 500	39.5	62.8
	5-C	30 500	32 500	35 500	67 500	37.5	58.8
	L-5	38 000	38 000	38 500	66 700	38.5	60.5
	8-C	28 000	30 500	36 000	65 500	34.0	64.0
	L8-1d	33 000	35 000	37 500	64 500	37.5	61.2
	L8-2d	36 500	36 500	38 000	65 000	38.0	61.6
	Average	33 300	34 600	37 300	65 600	37.5	61.5

*Gage length 8 in.

†Broke in punch mark.

TABLE 4
RESULTS OF COMPRESSION TESTS

Gage length 2 in. Approximate diameter $\frac{3}{4}$ in. Length of specimen $3\frac{1}{2}$ in. to 4 in. Stress in lb. per sq. in.

Material	Mark	Proportional Limit S_p	Useful Limit Point S_e	Yield Point S_y	Ultimate Strength S_u
Soft steel	M-C	25 500	25 500	26 200	46 400
	M-10	29 000	29 000	29 000	54 000
	M-S	26 000	26 000	27 200	45 000
	M-11	27 000	27 500	29 000	54 200
	M-T	26 500	26 500	27 000	47 400
	M-12	27 000	27 000	28 500	70 000
	Average	26 800	26 800	27 800	52 800
Mild steel	4	36 000	36 000	37 000	56 000
	8	36 000	36 000	36 500	61 000
	12	32 000	32 500	35 000	54 200
	16	35 000	35 000	35 500	58 700
	Average	34 800	34 900	36 000	57 500
Medium steel	4-4	37 000	40 000	46 000	80 800
	4-8	45 500	45 500	47 000	82 300
	Average	41 300	42 800	46 500	81 600
Vanadium steel	V-4	56 000	57 500	64 000	103 500
	V-8	56 000	58 500	64 000	111 500
	V-12	56 000	58 500	65 000	96 500
	V-10	52 500	55 000	64 000	106 000
	V-16	51 000	57 000	63 500	87 000
	Average	54 300	57 300	64 100	101 000
Nickel steel. Stress parallel to direction of rolling	P-3	42 000	46 000	49 000	65 200*
	P-4	42 500	47 000	50 500	99 500
	P-C	36 000	40 000	48 500	79 000
	P-D	37 000	38 000	48 500	86 600
	Average	39 400	42 800	49 100	88 400
Nickel steel Stress perpendicular to direction of rolling	C-A	38 500	43 000	47 500	89 500
	C-B	38 500	41 500	48 000	95 200
	C-4	38 500	40 500	50 000	92 500
	C-5	37 500	40 000	50 000	71 000†
	C-6	40 500	41 500	50 000	61 000†
	Average	38 700	41 300	49 100	92 400
Chrome-nickel steel	L-3	36 500	37 500	41 000	63 400
	L5-1d	39 000	39 000	40 000	70 200
	5-E	37 600	37 600	38 500	.....
	L-8	35 500	36 500	39 000	65 700†
	8-H	37 000	37 000	38 500	.....
	L5-2d	40 000	40 000	40 500	57 800†
	Average	37 600	37 900	39 600	64 300

*One end crushed. † Both ends crushed.

TABLE 5
RESULTS OF TORSION TESTS

Stress in lb. per sq. in. d = approximate outside diameter in inches

t = approximate wall thickness in inches.

l = gage length in inches.

Material	Type of Specimen	Mark	Proportional Limit S_p	Useful Limit Point S_e	Yield Point S_y	Modulus of Rupture S_r
Soft steel from 3½-in. bar.	Small solid $d = \frac{5}{8}$ $l = 2$	M-30*	15 400	15 400	17 400	.....
		M-3-0	15 400	18 300	19 900	.....
		M-1-D	14 100	14 900	16 800	.....
		M-2-D	13 900	15 400	18 500	.....
		M-3-D	14 600	14 600	15 800	.....
		31	14 000	16 500	18 600	60 500
		33	13 600	16 000	18 500	62 500
		34	14 400	17 700	19 000	61 500
		Average	14 400	16 100	18 100	61 500
	Small hollow $d = \frac{5}{8}$ $t = \frac{1}{32}$ $l = 2$	MS-1	12 300	13 600	19 200‡	.....
		MS-2	11 600	13 400	19 200‡	.....
		MS-3	10 300	12 700	17 000‡	.....
		35	10 700	15 500	21 100‡	30 200¶
		37	11 600	17 000	23 400‡	.....
		38	13 400	16 900	21 800‡	32 000¶
		Average	11 700	14 900	20 300‡	.....
	Large solid $d = 2\frac{7}{8}$ $l = 5$	M-1-1	12 300	14 500	20 200	.....
		M-4-3	12 900	14 800	20 500	.....
		M-6-2	13 200	15 500	20 200	.....
		M-S-10	14 000	14 400	20 400	.....
		M-E-0	18 600	19 400	20 800	.....
		Average	14 200†	15 700†	20 400	.....
	Large hollow $d = 2\frac{7}{8}$ $t = \frac{1}{8}$ $l = 5$	M-2-1	14 300	16 700	18 500	.....
		M-5-2	14 200	16 100	18 100	.....
		M-7-3	14 300	16 100	17 800	.....
		Average	14 300	16 300	18 100	.....
	Medium solid $d = 1\frac{3}{4}$ $l = 5$	MM	17 500	18 500	19 300	59 200
		MM-0	16 500	18 200	19 100	.....
		ME-0-1	16 000	17 700	18 900	.....
		Average	16 700	18 100	19 100	.....
	Medium hollow $d = 2\frac{3}{8}$ $t = \frac{3}{16}$ $l = 5$	MM-1	15 900	16 800	17 800	42 000¶
		MM-2	16 000	17 600	18 500	.....
		MM-3	17 600	18 400	19 200	.....
		Average	16 500	17 600	18 500	.....

*Gage length 8 in.

‡Yield point not well defined

†Results in error as explained in Section 9.

¶Collapsed.

TABLE 5—(CONTINUED)
RESULTS OF TORSION TESTS

Stress in lb. per sq. in. d = approximate outside diameter in inches.

t = approximate wall thickness in inches.

l = gage length in inches.

Material	Type of Specimen	Mark	Proportional Limit S_p	Useful Limit Point S_e	Yield Point S_y	Modulus of Rupture S_r
Mild steel from $\frac{1}{8}$ -in. bar Gage length 2 in.	Solid $d = \frac{5}{8}$	14	22 700	22 700	23 800	63 400
		2	22 200	22 200	24 200	60 200
		6	24 200	24 200	24 200	.....
		10	22 300	22 300	23 300	.....
		Average	22 900	22 900	23 900	61 800
	Hollow $d = 0.8$ $t = \frac{1}{8}$	H	21 000	21 000	21 000	.....
		K	21 000	21 000	21 000	.....
		L	20 900	20 900	20 900	57 000
		N	21 200	21 200	21 200	57 200
		Average	21 000	21 000	21 000	57 100
	Hollow $d = \frac{5}{8}$ $t = \frac{1}{16}$	1	22 600	22 600	23 600	47 600*
		5	20 500	20 500	22 100	.....
		9	20 600	20 600	22 900	.....
		13	21 600	21 600	23 000	.....
		Average	21 300	21 300	22 900	.....
	Hollow $d = 0.56$ $t = \frac{1}{32}$	A	20 000	20 000	21 800	55 000†
		B	20 100	20 100	21 400	33 000*
		C	19 200	19 200	20 500	.....
		D	19 800	19 800	20 500	.....
		E	19 400	19 400	21 200	.....
		Average	19 700	19 700	21 100	.....
Medium steel Gage length 2 in.	Solid $d = \frac{5}{8}$	4-2	30 900	31 600	33 800	79 300
		4-6	31 800	31 800	33 800	.....
		Average	31 400	31 700	33 800	.....
	Hollow $d = \frac{5}{8}$ $t = \frac{1}{16}$	4-1	27 100	27 600	29 300	56 500*
		4-5	26 600	27 400	29 700	69 200†
		Average	26 900	27 500	29 500	.....

*Collapsed.

†Sheared, rod filled center.

TABLE 5—(CONTINUED)
RESULTS OF TORSION TESTS

Stress in lb. per sq. in. d = approximate outside diameter in inches.

t = approximate wall thickness in inches

l = gage length in inches.

Material	Type of Specimen	Mark	Proportional Limit S_p	Useful Limit Point S_e	Yield Point S_y	Modulus of Rupture S_r
Vanadium steel from $\frac{7}{8}$ -in. bar Gage length 2 in.	Solid $d = \frac{5}{8}$	V-2	32 400	36 000	42 600	.....
		V-10	32 200	33 800	43 000	.....
		V-6	35 600	37 600	44 000	109 000
		V-14	34 200	37 300	45 000	.....
		V-1-V	37 700	39 400	46 500	.....
		V-2-V	35 100	39 200	46 500	102 000
		Average	34 500	37 200	44 600	105 800
	Hollow $d = 0.8$ $t = \frac{1}{8}$	V-B	37 200	37 200	43 000	.....
		V-C	36 200	38 100	42 500	.....
		V-20	39 200	39 200	43 000	.....
		V-21	37 200	38 000	42 000	.....
		V-22	37 700	37 700	42 500	96 000
		Average	37 500	38 000	42 600	.....
	Hollow $d = \frac{9}{8}$ $t = \frac{1}{16}$	V-1	36 000	38 000	43 000	.....
		V-5	32 800	35 000	43 500	74 300
		V-9	27 800	33 000	41 500	72 800*
		V-13	31 800	34 000	42 000	161 000†
		Average	32 100	35 000	42 500‡	.....
	Hollow $d = 0.56$ $t = \frac{1}{32}$	V-D	28 300	28 300	44 500	.....
		V-E	28 000	28 000	40 500	.....
		V-23	26 600	30 400	42 500	72 600†
		V-24	32 000	37 000	50 000	78 000†
		V-25	28 200	31 400	42 700	73 200†
		V-3-V	28 400	34 000	39 800	.....
		V-4-V	23 900	29 100	37 400	.....
		V-5-V	25 500	29 500	37 600	.....
		Average	27 600	30 900	41 900‡	.....

*Collapsed. †Sheared, rod filled center. ‡Yield point not well defined.

TABLE 5—(CONTINUED)
RESULTS OF TORSION TESTSStress in lb. per sq. in. d = approximate outside diameter in inches. t = approximate wall thickness in inches. l = gage length in inches.

Material	Type of Specimen		Mark	Proportional Limit S_p	Useful Limit Point S_e	Yield Point S_y	Modulus of Rupture S_r	
Nickel steel from slab 2 in. thick. Gage length 2 in.	Stress parallel to direction of rolling	Solid $d = \frac{5}{8}$	C-1	22 800	25 800	36 400	72 000	
			C-2	25 700	27 400	36 800	.....	
			C-3	26 000	27 600	.....	77 500	
			Average		24 800	26 900	36 600	74 800
		Hollow $d = \frac{5}{8}$ $t = \frac{1}{16}$	C-4	27 000	27 000	35 800	64 000†	
			C-5	23 500	23 500	34 400	.....	
			C-6	22 300	26 700	35 300	73 500‡	
			Average	24 300	25 700	35 200*	.....	
		Hollow $d = 0.56$ $t = \frac{1}{32}$	C-5d	21 000	23 300	34 200	.....	
			C-6d	21 500	24 800	34 200	.....	
			C-1d	23 900	24 400	34 800	.....	
			C-3d	22 300	24 000	36 200	.....	
	C-4d		21 000	23 500	35 500	.....		
	C-2d		22 300	25 700	36 000	.....		
	Average		22 000	24 300	35 200*	.....		
	Stress perpendicular to direction of rolling		Solid $d = \frac{5}{8}$	P-4	26 000	28 000	36 500	77 100
		P-5		26 000	30 000	40 500	.....	
				26 000	29 000	38 500*	.....	
		Hollow $d = \frac{5}{8}$ $t = \frac{1}{16}$	P-6	24 400	28 200	41 500	75 000†	
			P-7	24 200	27 200	37 000	76 000	
			Average	24 300	27 700	39 200*	.....	
		Hollow $d = 0.56$ $t = \frac{1}{32}$	P-8	Spoiled in testing				
			P-9	20 900	23 700	32 100	.....	
			P-10	20 600	23 400	31 500	.....	
			P-11	20 100	23 400	32 200	.....	
			Average	20 500	23 500	32 000*	.....	
Chrome-nickel steel. Gage length 2 in.		Solid $d = \frac{5}{8}$	L3-2d	24 100	24 700	26 300	.....	
			L3-1d	22 800	24 500	27 900	.....	
			L-5	24 100	25 200	28 000	62 200	
	L-8		25 200	26 200	27 200	.....		
	Average		24 100	25 200	27 400	.....		
	Hollow $d = \frac{5}{8}$ $t = \frac{1}{16}$	L8	23 800	23 800	24 800	51 200†		
		L5	22 300	22 300	23 600	.....		
		L3	22 300	22 300	24 300	51 600†		
		Average	22 800	22 800	24 200	.....		

*Yield point not well defined.

‡Sheared, rod filled center.

†Collapsed.

TABLE 6
AVERAGES OF THE STRENGTHS OBTAINED FROM THE INDIVIDUAL SPECIMENS IN TENSION, IN COMPRESSION,
AND IN SHEAR FOR EACH GRADE OF STEEL TESTED

Stress in lb. per sq. in.

Material	Kind of Stress	Number of Tests	Approximate Outside Diameter Inches	Gage Length Inches	Nominal Wall Thickness Inches	Proportional Limit S_p	Useful Limit Point S_e	Yield Point S_y	Ultimate Strength or Modulus of Rupture S_u or S_r	Elongation Per Cent	Reduction of Area Per Cent
Soft steel from $3\frac{1}{2}$ -in. bar	Tension	4	$\frac{3}{4}$	8 and 2	.....	21 000	25 000	28 400	55 400	28.9, 50.0	54.3
		3	$\frac{3}{4}$	2	.....	26 800	26 800	27 800	52 800	.....	....
	Shear	8	$\frac{5}{8}$	2 and 8	.....	14 400	16 100	18 100	61 500	.....	.....
		5	$2\frac{7}{8}$	5	.....	14 200*	15 700	20 400	.....	.....	.....
		3	$1\frac{3}{4}$	5	.....	16 700	18 100	19 100	59 200	.....	.....
		6	0.56	2	$\frac{1}{32}$	11 700	14 900	20 300	.....	.....	.....
Mild steel from $\frac{7}{8}$ -in. bar	Tension	3	$2\frac{1}{8}$	5	$\frac{1}{8}$	14 300	16 300	18 100	.....	.....	.....
		3	$2\frac{7}{8}$	5	$\frac{3}{16}$	16 500	17 600	18 500	.....	.....	.....
		4	$\frac{1}{2}$	2	.....	32 800	32 800	33 600	54 900	43.7	67.9
		4	$\frac{3}{4}$	2	.....	31 800	34 900	36 000	57 500	.....	.....
	Shear	4	$\frac{5}{8}$	2	.....	22 900	22 900	23 900	61 800	.....	.....
		4	0.8	2	$\frac{1}{8}$	21 000	21 000	21 000	57 100	.....	.....
Medium steel from $\frac{3}{4}$ -in. bars	Tension	4	$\frac{9}{16}$	2	$\frac{1}{16}$	21 300	21 300	22 900	.....	.....	.....
		5	0.56	2	$\frac{1}{32}$	19 700	19 700	21 100	.....	.....	.....
		2	$\frac{1}{2}$	2	.....	45 000	45 000	45 800	78 000	33.5	57.6
		2	$\frac{3}{4}$	2	.....	41 300	42 800	46 500	81 000	.....	.....
	Shear	2	$\frac{5}{8}$	2	.....	31 400	31 700	33 800	79 300	.....	.....
		2	$\frac{5}{8}$	2	$\frac{1}{16}$	26 900	27 500	29 500	.....	.....	.....

TABLE 6—(CONTINUED)
 AVERAGES OF THE STRENGTHS OBTAINED FROM THE INDIVIDUAL SPECIMENS IN TENSION, IN COMPRESSION,
 AND IN SHEAR FOR EACH GRADE OF STEEL TESTED
 Stress in lb. per sq. in.

Material	Kind of Stress	Number of Tests	Approximate Outside Diameter Inches	Gage Length Inches	Nominal Wall Thickness Inches	Proportional Limit S_p	Useful Limit Point S_e	Yield Point S_y	Ultimate Strength or Modulus of Rupture S_u or S_r	Elongation Per Cent	Reduction of Area Per Cent
Vanadium steel from $\frac{1}{8}$ -in. bar	Tension Compression	4	$\frac{1}{2}$	2	.....	52 500	55 900	60 400	109 000	24.0	47.0
		5	$\frac{3}{4}$	2	.....	54 300	57 500	63 100	101 000	.....	.....
	Solid Shear	6	$\frac{5}{8}$	2	.....	34 500	37 200	44 600	105 800	.....	.....
		5	0.8	2	$\frac{1}{8}$	37 500	38 000	42 600	96 000	.....	.....
	Hollow	4	$\frac{5}{8}$	2	$\frac{1}{16}$	32 100	35 000	42 500	.....	.....	.....
		8	0.56	2	$\frac{1}{32}$	27 600	30 900	41 900	.....	.....	.....
Stress parallel to direction of rolling	Tension Compression	2	$\frac{1}{2}$	2	.....	37 000	39 500	47 000	87 900	28.3	56.4
		4	$\frac{3}{4}$	2	.....	39 400	42 800	49 100	88 400	.....	.....
	Solid Shear	3	$\frac{5}{8}$	2	.....	24 800	26 900	36 600	74 800	.....	.....
		3	$\frac{5}{8}$	2	$\frac{1}{16}$	24 300	25 700	35 200	.....	.....	.....
	Hollow	6	0.56	2	$\frac{1}{32}$	22 000	24 300	35 200	.....	.....	.....
		3	$\frac{1}{2}$	2	.....	38 800	40 700	47 700	87 700	21.3	39.0
Stress perpendicular to direction of rolling	Tension Compression	5	$\frac{3}{4}$	2	.....	38 700	41 300	49 100	92 400	.....	.....
		2	$\frac{5}{8}$	2	.....	26 000	29 000	38 500	77 100	.....	.....
	Solid Shear	2	$\frac{5}{8}$	2	.....	24 300	27 700	39 200	.....	.....	.....
		4	0.56	2	$\frac{1}{32}$	20 500	23 500	32 000	.....	.....	.....
	Hollow	6	$\frac{1}{2}$	2	.....	33 300	34 600	37 300	65 600	37.5	61.5
		6	$\frac{3}{4}$	2	.....	37 600	37 900	39 800	64 300	.....	.....
Chrome-nickel steel from $\frac{3}{4}$ -in. bars	Tension Compression	4	$\frac{5}{8}$	2	.....	24 100	25 200	30 900	62 200	.....	.....
		3	$\frac{5}{8}$	2	$\frac{1}{16}$	22 800	22 800	24 200	.....	.....	.....
	Solid Shear	3	.....	2	.....	.....	.....	.....	.....	.....	.....

*In error, see Section 9 for discussion.

the fibers do not reach their yield points at the same time. The proportional limit, however, as found from the test of a solid cylindrical torsion specimen has, rather generally, been accepted as the correct shearing proportional limit of the material. Obviously, in the test of a solid cylindrical specimen, it is assumed that the first deviation of the stress-strain diagram from a straight line can be detected at the instant the proportional limit of the outermost fiber has been exceeded. With thin-walled, hollow cylindrical torsion specimens the shearing stress is nearly uniform over the section and the proportional limit represents very closely the correct proportional limit of the material. The results of the tests given in Table 5 show clearly that, although the test of a solid cylindrical torsion specimen is very satisfactory for indicating the general quality or character of the material and its reliability for resisting shear, it is not satisfactory for determining the real elastic shearing strength of the material.

TABLE 7

RELATION BETWEEN ELASTIC SHEARING STRENGTHS AS FOUND FROM
HOLLOW AND FROM SOLID TORSION SPECIMENS

Material		Ratio Shearing Strength, Hollow Specimens Shearing Strength, Solid Specimens		
		Proportional Limit	Useful Limit Point	Yield Point
Soft Steel	Small specimens	.813	.926	1.12*
	Large specimens	.857	.900	.947*
Mild steel		.860	.860	.882
Medium steel		.855†	.868†	.873
Vanadium steel		.800	.830	.940†
Nickel Steel	Stress parallel to direction of rolling	.886	.904	.962†
	Stress perpendicular to direction of rolling	.790	.810	.832
Chrome-nickel steel		.946†	.905†	.883

* Yield point of hollow specimens not well defined.

† Probably from 5 to 10 per cent too large because wall thickness of hollow specimens was $\frac{1}{16}$ in. instead of $\frac{1}{32}$ in.

‡ Yield point not well defined for either solid or hollow specimens.

In Table 7 are given values of the ratios of the elastic shearing strength as found from tests of hollow specimens to that found from

tests of solid specimens, the elastic strength being indicated by each of the three criteria; namely, proportional limit, useful limit point, and yield point. The results in Tables 6 and 7 justify the following conclusions:

(a) The shearing proportional limit and also the useful limit point obtained from tests with thin-walled hollow cylindrical torsion specimens is eight-tenths to nine-tenths (0.8 to 0.9) of the proportional limit found from solid cylindrical specimens of the same material and a value of eighty-five hundredths (0.85) may be taken with reasonable accuracy for the ratio of the elastic shearing strength found from thin-walled hollow specimens to the similar strength obtained from solid specimens.

(b) The yield point obtained from hollow thin-walled torsion specimens is eighty-five hundredths to nine-tenths (0.85 to 0.9) of the yield point found from solid cylindrical torsion specimens of the same material. This result applies, of course, only to the materials which have a well defined yield point.

The elastic shearing strength (S_p , S_e , and S_u in Table 5) was calculated in each case from the usual formula, $S = \frac{Tc}{J}$ in which T is the twisting moment (inch pounds), J is the polar moment of inertia (inch⁴), and c is the radius of the specimen (inch).

By making use of the conclusions stated above a solid cylindrical torsion specimen may be used with considerable confidence to obtain test results from which the true elastic shearing strength may be calculated for steel likely to be used in general structural or machine construction, although the character or development of the elastic breakdown may be obscured in the test of a solid specimen, as is discussed in the next section. The test results from a solid specimen may also be used, of course, to judge of the general properties, quality, and reliability of the material.

The correct value of the ultimate shearing strength of a material can not be obtained, of course, from a torsion test of a solid specimen, although the modulus of rupture, for many purposes, is a satisfactory indication of the general quality of the material and of the shearing resistance against rupture. It is difficult also to determine the ultimate strength from a thin-walled hollow torsion specimen because the specimen fails by collapsing (see Fig. 3). An attempt was made to

prevent collapsing by filling the core of the hollow cylindrical specimen with a close (but not tight) fitting rod. It was found, however, that torque was transmitted to the rod. Two rods were then used, one extending in from each end, with somewhat better results. Although the results given in Table 5 on this point are not sufficient for definite conclusions, they indicate that the true ultimate shearing strength is from eight-tenths to nine-tenths (0.8 to 0.9) of the modulus of rupture as obtained from a test of a solid cylindrical torsion specimen.

It will be noted that in the case of the large torsion specimens of soft steel there seems to be some inconsistency in the results as given in Table 5. For instance, the proportional limit and the useful limit point is less for the large solid specimens than for the hollow specimens; these results are contrary to the above conclusions. It was found that binding occurred at the collar of the roller bearing of the stationary head of the torsion machine, particularly at the relatively large twisting moments required for the large solid specimens. This defect was remedied and the diameter of the remaining solid specimens was reduced to $1\frac{3}{4}$ inches so as to use about the same load range on the machine as was used with the hollow specimens. The results, therefore, of the tests with the large solid specimens (diameter $2\frac{7}{8}$ inches) are not considered further.

The test results of all the small torsion specimens and also of the large specimens of soft steel show that the wall thickness must be thin to obtain the correct elastic shearing strength of the material. The wall thickness of the medium carbon steel and of the chrome-nickel steel specimens was $1/16$ inch. From the torsion tests of the other materials in which both $1/16$ -inch and $1/32$ -inch wall thickness were used, it appears that the correct shearing strength of the medium steel and the chrome-nickel steel is from 5 to 10 per cent lower than that given in Table 6. The ratios as given in Table 7 for these two materials are, therefore, probably somewhat too large.

10. *Characteristics of Elastic Shear Failure.*—Ductile steel rods or specimens from rolled shapes (any specimens from pieces which have been worked considerably in the forming process) when tested in tension, show a rather sudden or abrupt elastic breakdown culminating in a well defined yield point. Steel which has not been worked much, such as the interior material of large rolled bars, does not show such a sudden failure but gives a more gradual curve for the stress-

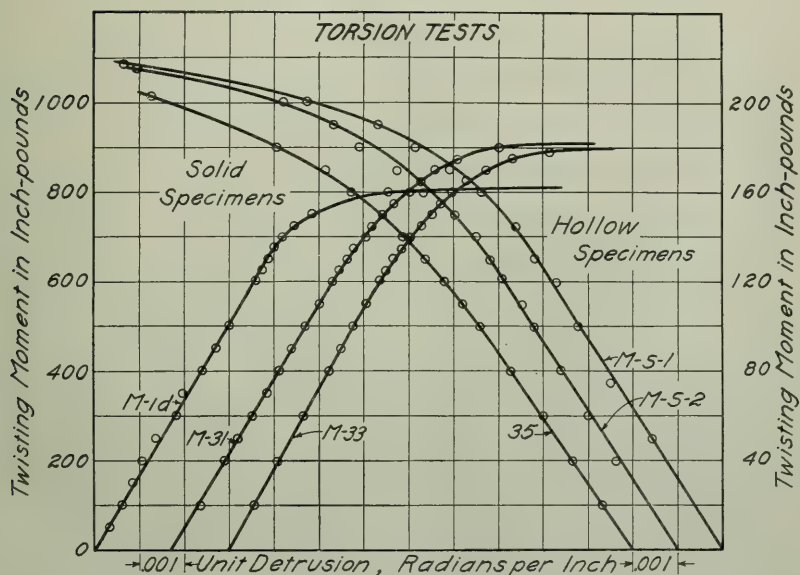
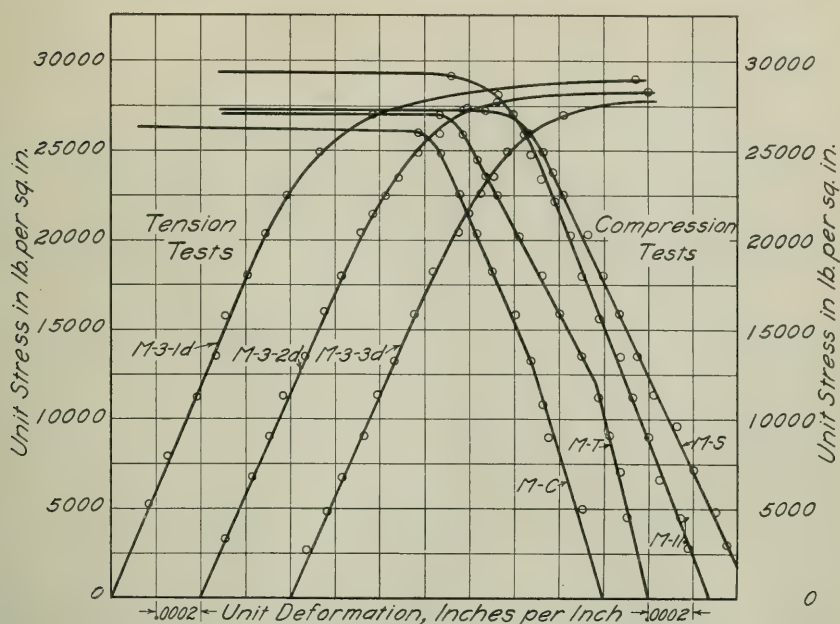


FIG. 6. REPRESENTATIVE STRESS-STRAIN AND MOMENT-STRAIN (TORSION) DIAGRAMS FOR SOFT STEEL—SMALL SPECIMENS

strain diagram (see Figs. 6 and 7 for stress-strain curves for the soft steel from the $3\frac{1}{2}$ -inch bar). This point is discussed further in a later section.

The elastic shearing failure of a solid cylindrical specimen of ductile steel when tested in torsion is also rather abrupt with a well defined yield point (see Fig. 8). These facts, backed by the maximum shear theory, by the form of a tensile fracture (cup shaped) and by the slip-lines produced at or near the yield point under repeated load-

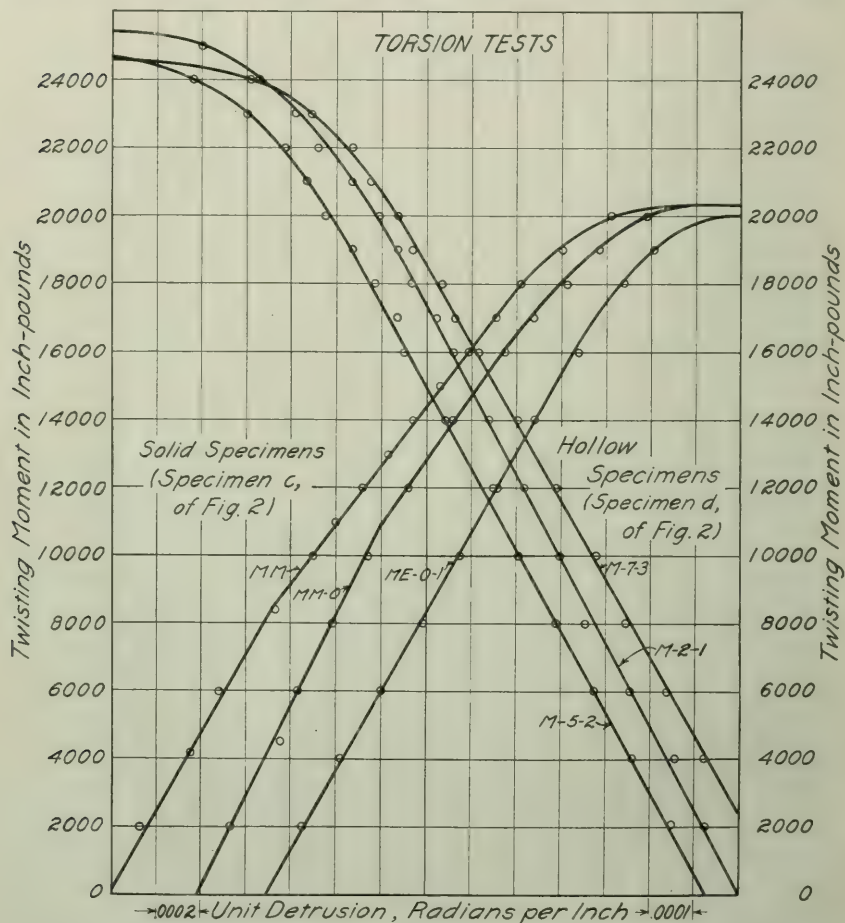


FIG. 7. REPRESENTATIVE MOMENT-STRAIN (TORSION) DIAGRAMS FOR SOFT STEEL—LARGE SPECIMENS

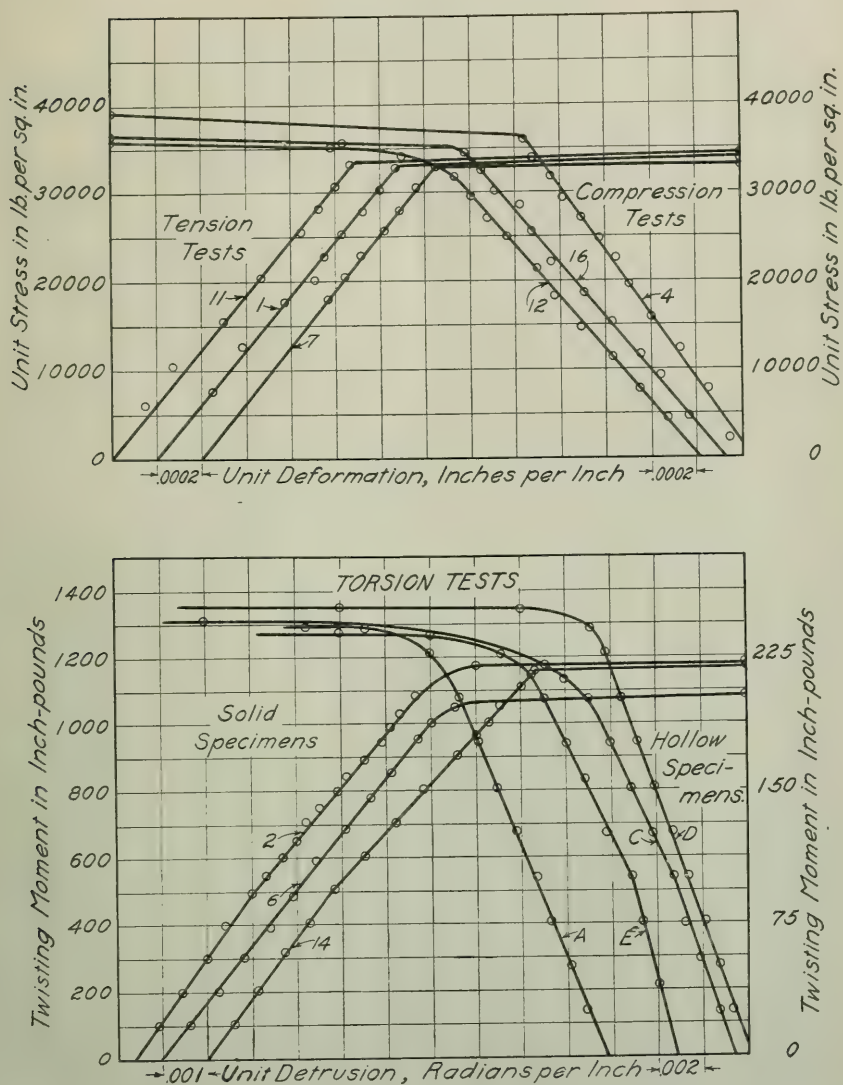


FIG. 8. REPRESENTATIVE STRESS-STRAIN AND MOMENT-STRAIN (TORSION) DIAGRAMS FOR MILD STEEL

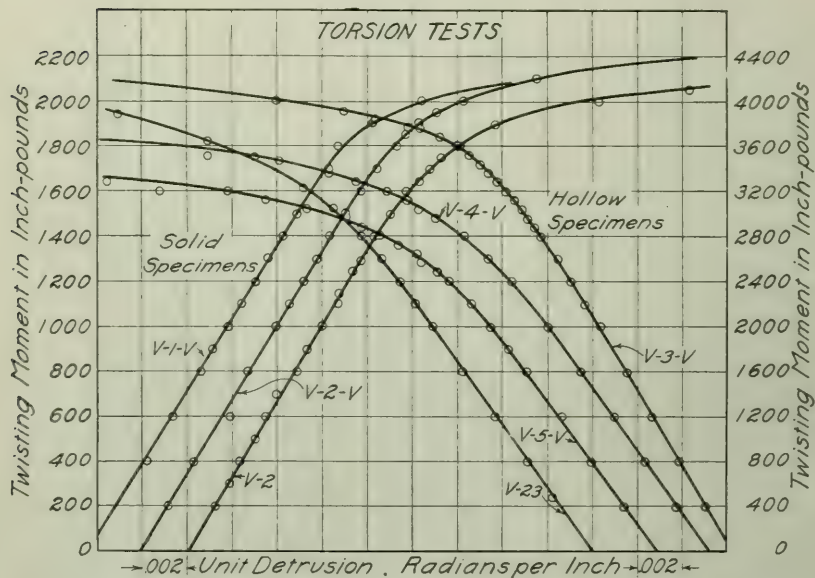
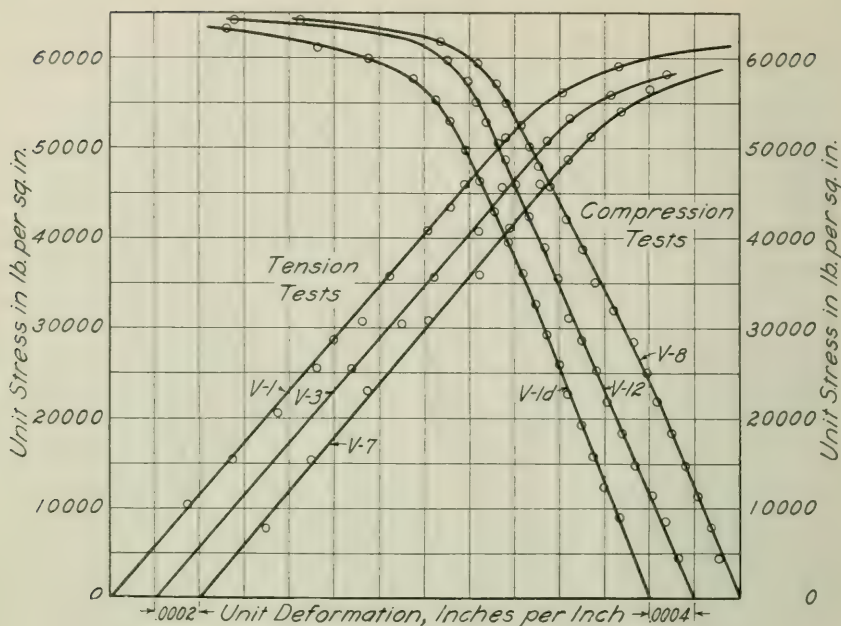


FIG. 9. REPRESENTATIVE STRESS-STRAIN AND MOMENT-STRAIN (TORSION) DIAGRAMS FOR VANADIUM STEEL

ing, have often been used to explain the elastic tensile failure as really a shear failure over an inclined section. And since in a tension test the maximum shearing unit-stress over a section inclined at 45° is one-half of the tensile unit-stress, it has been urged that the elastic shearing strength may best be found from a tension test. Before discussing the experimental data from which the ratios between the elastic shearing and tensile strengths have been found (see next section), it will be well to examine the general character of the elastic shear failure as indicated by the stress-strain diagrams of the thin-walled hollow torsion specimens. From Figs. 6 to 9 which are representative and typical stress-strain diagrams for some of the materials, it will be noted that in most cases the shearing breakdown of elastic action of the various materials is very gradual. In fact, in most cases, it is more gradual than the failure of the elastic action in a tension specimen. It seems difficult, therefore, to account for a tensile elastic breakdown as a failure due to shear, or to have confidence in the use of a tension test for the determination of the elastic shearing strength except for an approximate value. It will also be observed that the solid torsion specimens show a more abrupt elastic failure than a hollow thin-walled specimen of the same material; this fact indicates that the proportional limits of the outer fibers have been somewhat exceeded before a deviation of the stress-strain diagram from a straight line can be detected. This has already been discussed in the section on *Shearing Strength*. The stress-strain diagrams for the medium carbon steel and for the nickel and chrome-nickel steel (not shown) indicate the same characteristics as are shown in Figs. 6 to 9. It appears, therefore, that, contrary to the usual assumption, the shearing breakdown of elastic action of ductile and semi-ductile steel is more gradual than the corresponding tensile or compressive failure.

11. *Ratio of Elastic Shearing Strength to Elastic Tensile Strength*.—Table 8 gives the ratios of the elastic shearing strengths to the elastic tensile strengths for the various materials tested, the elastic strengths being indicated by the proportional limits, the useful limit points, and the yield points. It will be noted from a study of Table 8 that the shearing proportional limits of most of the steels tested are from fifty-five to sixty-five hundredths (0.55 to 0.65) of the tensile proportional limits and that the same statement may be made in the case of the useful limit points. The two materials for which the ratio

TABLE 8
RATIOS OF ELASTIC STRENGTHS IN SHEAR AND TENSION AND ALSO IN TENSION AND COMPRESSION

Material	Ratio Shearing Proportional Limit Tensile Proportional Limit		Ratio Shearing Useful Limit Point Tensile Useful Limit Point		Ratio Shearing Yield Point Tensile Yield Point		Ratio Tensile Elastic Strength Compressive Elastic Strength			
	Hollow Specimens	Solid Specimens	Hollow Specimens	Solid Specimens	Hollow Specimens	Solid Specimens	Proportional Limit	Useful Limit Point	Yield Point	
Soft steel	Small specimens	.558	.685	.596	.645	.638	.715*	.638		
	Large specimens	.680	.795	.652	.724	.672	.638		.933	1.04
Mild steel		.600	.698	.600	.698	.682	.628	.943	.940	.932
Medium steel		.597†	.698	.611†	.705	.738	.644	1.09† or .989	1.05† or 1.01	.965
Vanadium steel		.526	.657	.553	.637	.739	.694*	.950	.972	.943
Nickel steel	Stress parallel to direction of rolling	.594	.670	.615	.681	.780	.749	.939	.923	.956
	Stress perpendicular to direction of rolling	.529	.670	.577	.710	.807	.671	1.00	.985	.972
Chrome-nickel steel		.642†	.683	.650	.698	.814	.637	.886	.887	.942

*Yield point of hollow specimens not well defined.

†Probably 5 to 10 per cent too large since hollow specimens with $\frac{1}{16}$ in. wall thickness were used instead of $\frac{1}{32}$ in.

‡Probably in error: only two specimens tested in compression one of which gave very low results (see Table 4).

varies most from the average are the soft steel (large specimens) and the vanadium steel. Owing to the fact that the tension specimens of soft steel were made by quartering a 14-inch length of the 3½-inch bar, they contained much of the inner or "heart" material of the large bar, while the large hollow specimens contained none of the "heart" material. It is doubtful, therefore, whether the tension specimens should be considered as of the same material as the large hollow specimens. Greater variation also was noted in the test results with the soft steel specimens than with the other materials (see section 13 for further discussion). In connection with the vanadium steel it should be stated that due to the greater hardness of the vanadium steel, it was more difficult to produce a smooth hole in drilling out the center of the hollow specimens of this material than of the softer materials. The wall thickness as measured, therefore, may be slightly too large, because the grooves or tool marks were, perhaps, not properly taken into account. If this statement is true, the values of the ratio for vanadium steel are somewhat too small. This statement may also explain the somewhat greater variation in the values of elastic strengths obtained from the thin-walled (1/32 inch thick) vanadium specimens than in those obtained from the corresponding specimens of most of the other materials. It may also account for the greater difference between the results obtained with 1/32-inch and 1/16-inch wall thicknesses for vanadium steel than for the other steels. It is possible, however, that the ratio for vanadium steel is somewhat lower than for the other steels tested.

With these facts in mind it is felt that a study of Table 8 justifies the conclusion that the elastic shearing strength of steel likely to be used in general construction of machines or structures is close to six-tenths (0.6)* of the elastic tensile strength, instead of one-half (0.5) of the elastic tensile strength as assumed in the maximum shear theory of combined stress as expressed by Guest's law. In other words, ductile or semi-ductile steel will not suffer elastic breakdown when the shearing unit-stress developed is one-half of the elastic tensile strength of the material; hence the field in which the maximum strain theory may hold is not as limited as would be the case if the elastic shearing strength were one-half of the tensile strength. The influence of this fact upon the design of machines or structures under combined loading such as thick cylinders, flat plates, crank shafts, girders, etc., can

*The value of six-tenths is also found by Becker with biaxial loading, see Bulletin No. 85, p. 43, Engineering Experiment Station, University of Illinois.

TABLE 9
RESULTS OF EARLIER EXPERIMENTS

Experiments by Platt and Haywood*			Experiments by E. B. Turner†		
Materials	Tensile Yield Point lb. per sq. in.	Ratio Tension, Yield Point Tension, Yield Point	Materials	Tensile Proportional Limit	Ratio Tension, Proportional Limit Tension, Proportional Limit
Wrought iron (N. Crown)	33 700	.508	Mild steel‡ (0.15% C)	31 000	.519
Wrought iron (S. C. Crown)	38 400	.597	Mild steel§ (0.32% C)	42 300	.577
Rivet iron	37 700	.615	Tool steel§ (1.25% C)	67 700	.568
Siemens Martin steel	37 700	.604	Nickel steel§ (3.01% Ni.)	81 200	.503
Bessemer steel	69 800	.617	Experiments by E. L. Hancock**		
Crucible steel	69 600	.623	Steel tubing	24 000	.500
Rivet steel	40 000	.571	Nickel steel	70 300	.497
Cast steel	38 000	.604	Mild carbon steel	47 000	.649
			Steel (Seabro)	64 600	.451
			Carbon steel	35 500	.688
			Rivet steel	38 900	.602
			Nickel steel	56 000	.643
			Steel tubing	17 000	.677
			Steel tubing	28 000	.576
			Steel tubing	20 000	.600

*Proc. Institution of Civil Engineers, Vol. 90, p. 382, 1888.

†Yield point found by drop of beam.

‡Engineering (London), February 12, 1909, and July 28, 1911.

§Specimens made of thin-walled tubing.

§Specimens made of small solid rods, $\frac{3}{4}$ in. (tension) and 0.33 in. (torsion).

**Proc. A. S. T. M., p. 376, 1908.

not be discussed here. It makes possible more efficient and economical use of material, under certain conditions, than would be the case if the shearing strength were one-half of the tensile strength.

12. *Results of Earlier Experiments.*—Results of tests of various grades of steel in simple tension and simple torsion made by Platt and Hayward, by L. B. Turner, and by E. L. Hancock are given in Table 9. Platt and Hayward used solid bars $1\frac{1}{2}$ inches in diameter for both tension and torsion tests. The yield point as found by the drop of the beam was used as the elastic strength for both tension and torsion. Two specimens in tension and three in torsion were used for each material. Initial strains were first taken out by repeated loadings. Considering the method of determining the elastic strength and the fact that the elastic strength was of secondary importance in the investigation, the results for the ratios of the elastic strengths in torsion and in tension as found by Platt and Hayward (Table 9) agree well with the values of the same ratio as herein recorded (Table 8).

In the tests by Turner the specimens of mild steel with 0.15 per cent C. were made from annealed weldless steel tubes with an outside diameter of 1 inch and wall thickness of 0.022 inch (No. 24 B.W.G.) for both tension and torsion tests. The wall thickness was not measured for each specimen but an average thickness was determined for twelve short (1 inch) portions cut from three tubes taken at random. The mean thickness was found by first weighing the portions in air and then in water. There was considerable variation in thickness from point to point around a section of a cut portion; in some cases an eccentricity was perceptible to the naked eye. Considerable variation in thickness was shown among the results of the individual specimens. Twenty-one specimens of this particular material were tested.

The specimens for the other three materials tested by Turner were solid $\frac{3}{8}$ -inch rods for the tension tests and $\frac{3}{8}$ -inch rods turned down to 0.33-inch diameter for a length of $3\frac{1}{2}$ inches for the torsion tests. The number of specimens was much less than for the steel tubing. All of the specimens were annealed. Nickel steel specimens showed the greatest variation in the results of the individual specimens.

The yielding of all the specimens was very sudden. In all cases the proportional limit and the yield point coincided. This result is quite contrary to the results found in the tests which have already been explained in this bulletin.

When the method of determining the wall thickness of the hollow specimens, the small size of the solid torsion specimens, and the difference in the method of experimenting are considered, the ratios of the elastic strengths in torsion and in tension as found by Turner (Table 9) are in fair agreement with the values of the same ratio as found from the tests herein described (Table 8).

The results of the tests by Hancock show considerable variation. No description of the material is given other than its name in Table 9 and nothing is stated as to the kind or number of specimens used or the method of testing except that the proportional limit was used as a measure of the elastic strength. The results indicate a fair agreement with the results herein recorded for most of the materials, although the low values for the ratio of shear (torsion) to tension for some of the materials is not found by any of the other experimenters.

The values for the ratio of the elastic strengths in tension and in shear as indicated in tests with combined loading have not varied much from 0.6. Becker* found values of 0.59 and 0.62 for two grades of steel tubing. Scoble's† tests are the only ones which indicate that the ratio is less than 0.5 and his criterion of elastic strength and method of experimenting seem somewhat unusual.

A study of the earlier experiments discussed above bear out, in the main, the conclusions already stated for the results presented in this bulletin; namely, that the elastic shearing strength of ductile and semi-ductile steel varies but little from six-tenths (0.6) of the elastic tensile strength.

13. *Ratio of Elastic Tensile Strength to Elastic Compressive Strength.*—The elastic strength in tension and in compression for ductile steels is usually considered to be the same. This assumption is sufficiently accurate for many purposes. In the problems of combined stress and in built-up compression members, however, it is important to know accurately the relation between the elastic tensile and compressive strengths and particularly to know how the strengths are affected by mechanical treatment of the steel such as the amount of working during the rolling process. Tables 6 and 8 indicate that the elastic compressive strength of ductile steel is somewhat greater than the elastic tensile strength except in the case of soft steel. It is clear from a study of Table 8 that the amount of working or rolling has a

*Bulletin No. 85, Engineering Experiment Station, University of Illinois.

†Philosophical Magazine, May, 1906.

marked effect upon the elastic tensile and compressive strengths of steel. Table 8 indicates that steel which has been rolled into comparatively thin plates or small shapes has an elastic compressive strength approximately 5 per cent greater than the elastic tensile strength whether the elastic strength is judged from the proportional limit, useful limit point, or yield point. In the case of soft steel from the $3\frac{1}{2}$ -inch bar which represents material with relatively little working in the rolling process, the compressive proportional limit is much greater (27 per cent) than the tensile proportional limit, while the yield point in compression is somewhat less (4 per cent) than the yield point in tension (see Fig. 6 and Table 8). It appears, therefore, that the criterion of elastic strength may be of much importance, that the tension test so generally used to judge of the elastic properties of steel is not wholly reliable, and that it may be necessary to resort to auxiliary compression tests for material to be used under certain conditions of combined stress and for critical compression members,* at least, until test results and the treatment received by the material can be correlated through more extensive experimental investigations. To what extent the increased compressive strength due to rolling may be attributed to compacting, causing a denser material, or attributed to the arrangement of the crystals of the constituent elements in steel or to other factors is not definitely known. The problem offers opportunity for fruitful experimental work. It was noted that the breakdown of elastic action in compression is fully as gradual as that of the corresponding tensile failure (in most cases more so) except in the case of soft steel. This fact suggests that compacting of steel may be an important factor in determining its strength. The maximum shear theory (Guest's law) of the breakdown of elastic action assumes that the elastic tensile and compressive strengths are the same. The results of Table 8 give further evidence that Guest's law is not an accurate interpretation of the elastic failure of all ductile steel.

14. *Effect of Direction of Rolling.*—It is generally recognized that the direction of rolling of hot-rolled steel influences the grain or

*In the tests of large built-up columns conducted by Bureau of Standards for the Committee on Steel Columns and Struts of the American Society of Civil Engineers, (see Proc. A. S. C. E. Dec., 1917) it was found that the columns built up of $\frac{1}{2}$ -inch to $\frac{3}{8}$ -inch material showed a considerably lower strength in most cases than those of $\frac{3}{8}$ -inch material. Compressive tests on specimens sawed from the thick portions showed a decrease in the compressive yield point of 6000 pounds per square inch as compared with the tensile yield point of the same material, while the compressive yield point of specimens sawed from the thin portions was nearly the same as the tensile yield point.

crystal growth or formation, by making the grains or crystals longer in the direction of rolling. It is usually assumed, however, that the elastic strength of the material is not affected by the direction of rolling or, in other words, that the elastic strength is the same in all directions. Some experimental results were obtained on this point in the case of nickel steel. As already stated the specimens of nickel steel were cut from a rolled slab 2 inches thick by $7\frac{1}{2}$ inches wide. From this slab some specimens were cut with their longitudinal axes parallel to the direction of rolling and others with their axes perpendicular to the direction of rolling. Specimens whose axes are parallel to the direction of rolling, when tested in torsion, develop shearing stress perpendicular to the direction of rolling and when tested in tension and compression, of course, develop stress parallel to the direction of rolling, while the reverse is true for the specimens whose axes are perpendicular to the direction of rolling.

The results given in Tables 3, 4, 5, and 6 for nickel steel, although not entirely consistent, fail to indicate any systematic influence of the direction of rolling on the elastic strength of the material either for tension, compression, or shear. However, the ductility as measured by the ultimate tensile elongation and reduction of area shows a marked effect of the direction of rolling. The effect on the ductility is also very noticeable in the appearance of the fracture. While the values given in Table 8 for nickel steel seem to indicate some effect of direction of rolling, a study of the more detailed data in Tables 3 to 6, reveals little if any effect on the elastic strength. The ultimate strengths in tension, in compression, and in shear also show no influence of the direction of rolling. Whether much thinner material such as used for boiler plates, rolled sections, etc., would show more effect of the direction of rolling is not known.

15. *Summary.*—The severe uses to which carbon and alloy steels are put in some phases of engineering, as for example, in automobile and in aeroplane construction, have developed a need for more detailed knowledge of the action of steel, both within and beyond the elastic limit, under various types of stress, as well as of the factors which affect the physical properties of the material. This need, in time, may require some modifications in the tests of the materials and in the methods of interpreting the tests. The following brief summary of the chief points brought out by this investigation are offered as a con-

tribution toward filling part of this need. The conclusions apply to hot-rolled carbon and alloy steels which are representative of those likely to be used in general structural and machine construction.

(1) The correct value of the elastic shearing strength of steel as measured by the proportional limit or the useful limit point may be determined from a torsion test of a hollow thin-walled cylindrical specimen. The correct value of the yield point in shear is also shown in the test of a hollow thin-walled torsion specimen.

(2) The correct value of the elastic shearing strength of steel as measured by the proportional limit or the useful limit point may be taken, with reasonable accuracy, as eighty-five hundredths (0.85) of the elastic strength obtained from a torsion test of a solid cylindrical specimen. The correct value of the yield point for the more ductile materials is slightly more than eighty-five hundredths (0.85) of the yield point obtained from a test of a solid torsion specimen.

(3) A solid cylindrical torsion specimen, therefore, may be used to obtain test results from which the correct value of the elastic shearing strength and the shearing yield point of steel may be calculated by the use of a correction factor, although the character or progress of the breakdown of the elastic action may be obscured in the test of the solid specimen. Test results obtained from a solid specimen may also be used, of course, to judge of the general properties, quality, and reliability of the material.

(4) The correct value of the elastic shearing strength of steel as measured by the proportional limit or the useful limit point is from fifty-five to sixty-five hundredths (0.55 to 0.65) of the elastic tensile strength and may be taken with reasonable accuracy as six-tenths (0.6) of the elastic tensile strength. The maximum shear theory of the failure of elastic action of ductile steel (sometimes called Guest's law) is, therefore, not an accurate statement of the law of elastic breakdown, since Guest's law assumes that the elastic shearing strength is one-half (0.5) of the elastic tensile strength. The maximum shear theory as expressed by Guest's law, however, is of much use in obtaining approximate results.

(5) Contrary to the general belief, the breakdown of the shearing elastic action of ductile and semi-ductile steel as found in these tests is gradual; more gradual, as a rule, than the failure of elastic action in a tension specimen.

(6) The amount of hot-rolling received by steel may have a marked effect upon the relation of the elastic tensile and compressive strengths. For the material from $\frac{3}{4}$ -inch and $\frac{7}{8}$ -inch bars, the elastic compressive strength is somewhat greater (about 5 per cent) than the elastic tensile strength whether the elastic strength is measured by the proportional limit, useful limit point, or the yield point. For the material from the $3\frac{1}{2}$ -inch bar, the compressive proportional limit is very much greater (27 per cent) than the tensile proportional limit, while the compressive yield point is somewhat less (4 per cent) than the tensile yield point.

(7) It appears, therefore, that the choice of the criterion of elastic strength may be of considerable importance in some cases, and that the usual tensile test of material may require supplementary compressive tests or a better correlation between test data and the amount of treatment received during rolling, before the elastic properties of the material as obtained from tensile test data can be relied upon.

(8) The elastic strength and ultimate strength of steel in tension, in compression, and in shear is affected little, if any, by the direction of rolling in the case of a slab 2 inches thick, although the ductility, as measured in tension tests by the percentage of elongation and percentage of reduction of area, is materially less when the stress is perpendicular to the direction of rolling than it is when the stress is parallel to the direction of rolling.

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